

# **Third DOE Workshop on Heavy Vehicle Aerodynamics**

**November 14, 1999**

## **Sponsor**

**DOE Office of Transportation Technology, Office of Heavy Vehicle Technology**

## **Purpose and Scope**

**Presentation of DOE goals and activities - program plan, progress, and results**

**Industry perspective - John Horne, Chairman, President & CEO,  
Navistar International Transportation Corp.**





Department  
of  
Energy


# Reducing Aerodynamic Drag for Class 7-8 Trucks

<http://energy.llnl.gov/aerodrag>

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November 14, 1999

University of California  
 Lawrence Livermore  
National Laboratory

 Sandia  
National  
Laboratories

USC  
 UNIVERSITY  
OF SOUTHERN  
CALIFORNIA

 Caltech  
California Institute of Technology

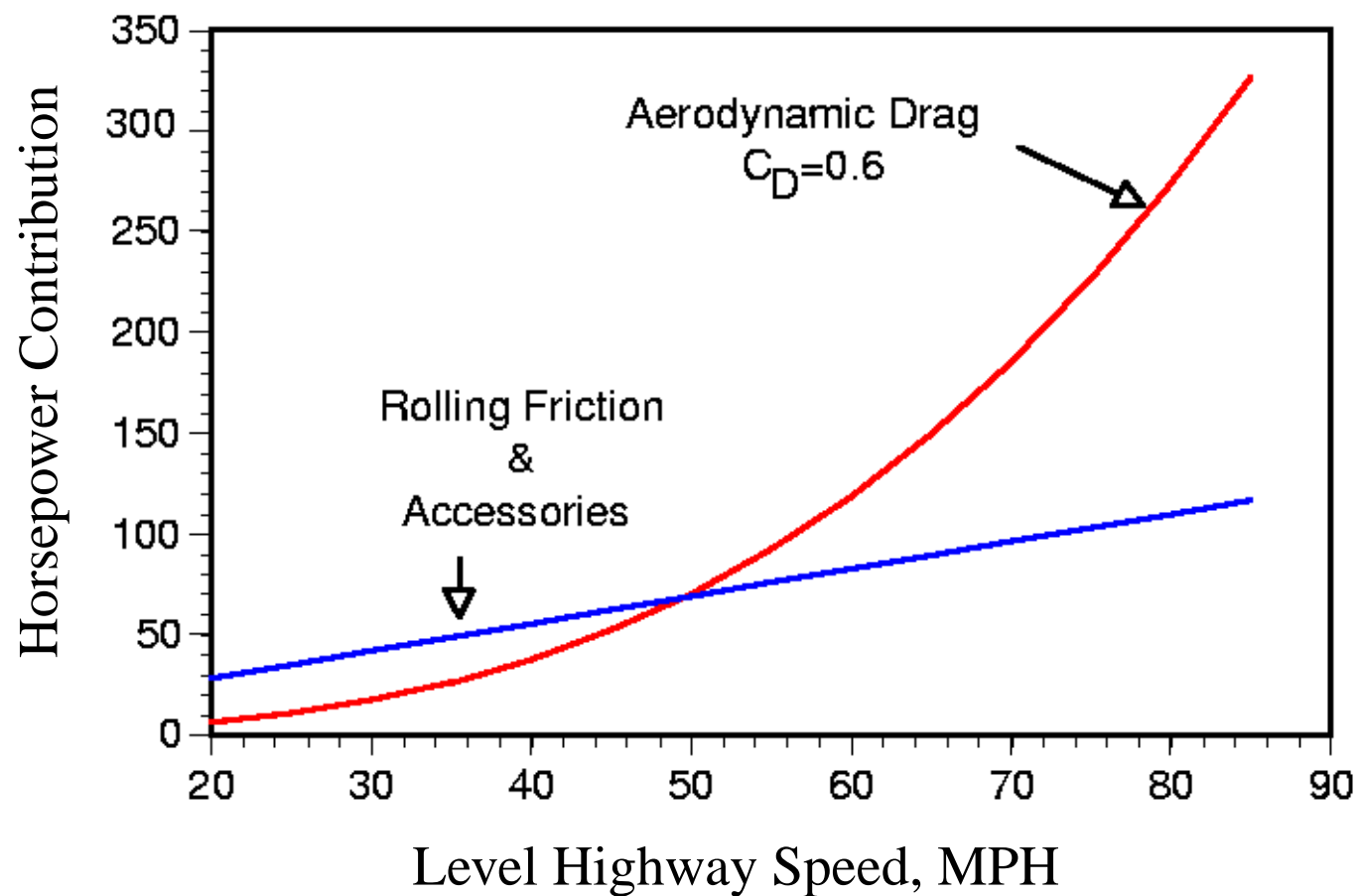
 National  
Aeronautics &  
Space  
Administration

Georgia  
Tech  Research  
Institute

**At 70 mph, 65% of the total energy expenditure is in overcoming aerodynamic drag.**

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**Typical Class 8 tractor-trailer**



## **A workshop in January 1997 was the project kick-off.**

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### **DOE Workshop on Heavy Vehicle Aerodynamic Drag, Phoenix, Arizona**

#### **Purpose**

**Forum for communication**

**Determine industry's current practices and technical needs**

**Present national lab's and universities' state-of-the-art expertise**

#### **Conclusions**

**Trailer design should be the focus of near-term efforts**

**An integrated tractor-trailer design is needed**

**Advanced computational tools are needed**

#### **Action Items**

**Form an *Advisory* Committee of industrial participants**

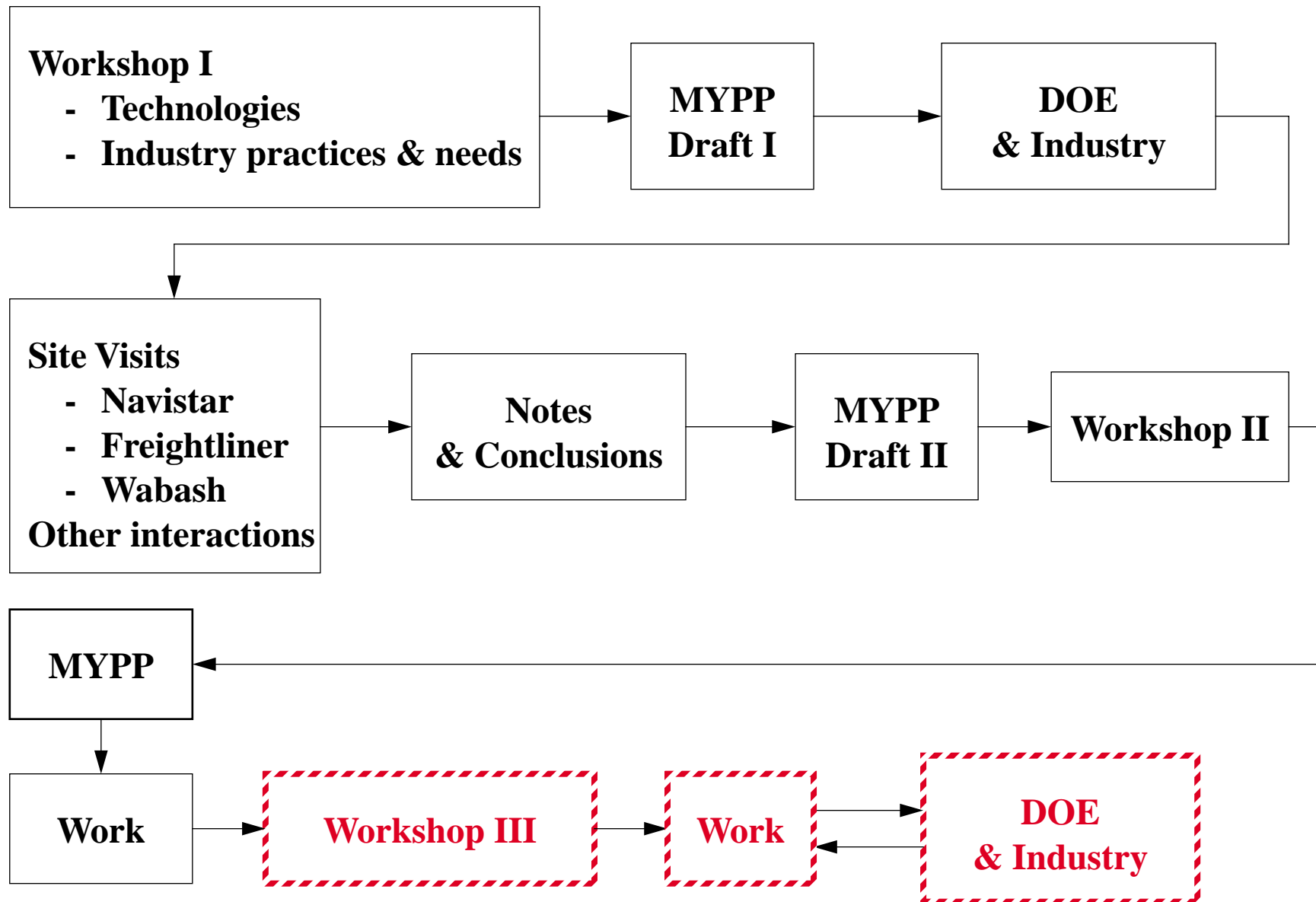
**Form a *Technical* Committee to construct MYPP with industry guidance**

**Follow-up workshop to finalize MYPP**

## The Technical Committee's task was to develop a MYPP.

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### Evolution of MYPP



# **The truck industry relies on wind tunnel and field experiments for aerodynamic design and analysis.**

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## **Wind Tunnel Testing**

**Costly detailed models**

**Expensive tunnel use**

**Trial-error approach to determine drag effects**



**Cabover Engine**

## **Field Testing**

**Performed by both manufacturer and fleet operators**



**Conventional**

## **Issues**

**A tractor is paired with several different trailers**

**Almost no aero design interaction between tractor and trailer manufacturers**

**The effects of design changes on drag are not well understood and computational guidance is needed**

**The project focus is based on industry needs and consideration of current technology, funding, and DOE interests.**

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#### **DOE and National Laboratory interest**

**Reduce heavy vehicle drag -> reduce fuel consumption and emissions**

**R&D for DOE programs**

#### **Industry needs**

**Advanced validated computational tools and experimental techniques**

**Understand the effects of design changes**

**Simulate fully-integrated tractor-trailers**

**Design improvements for drag reduction**

#### **Current technology - CFD is hard!**

**Direct numerical simulation (DNS) - required resolution makes problem too big**

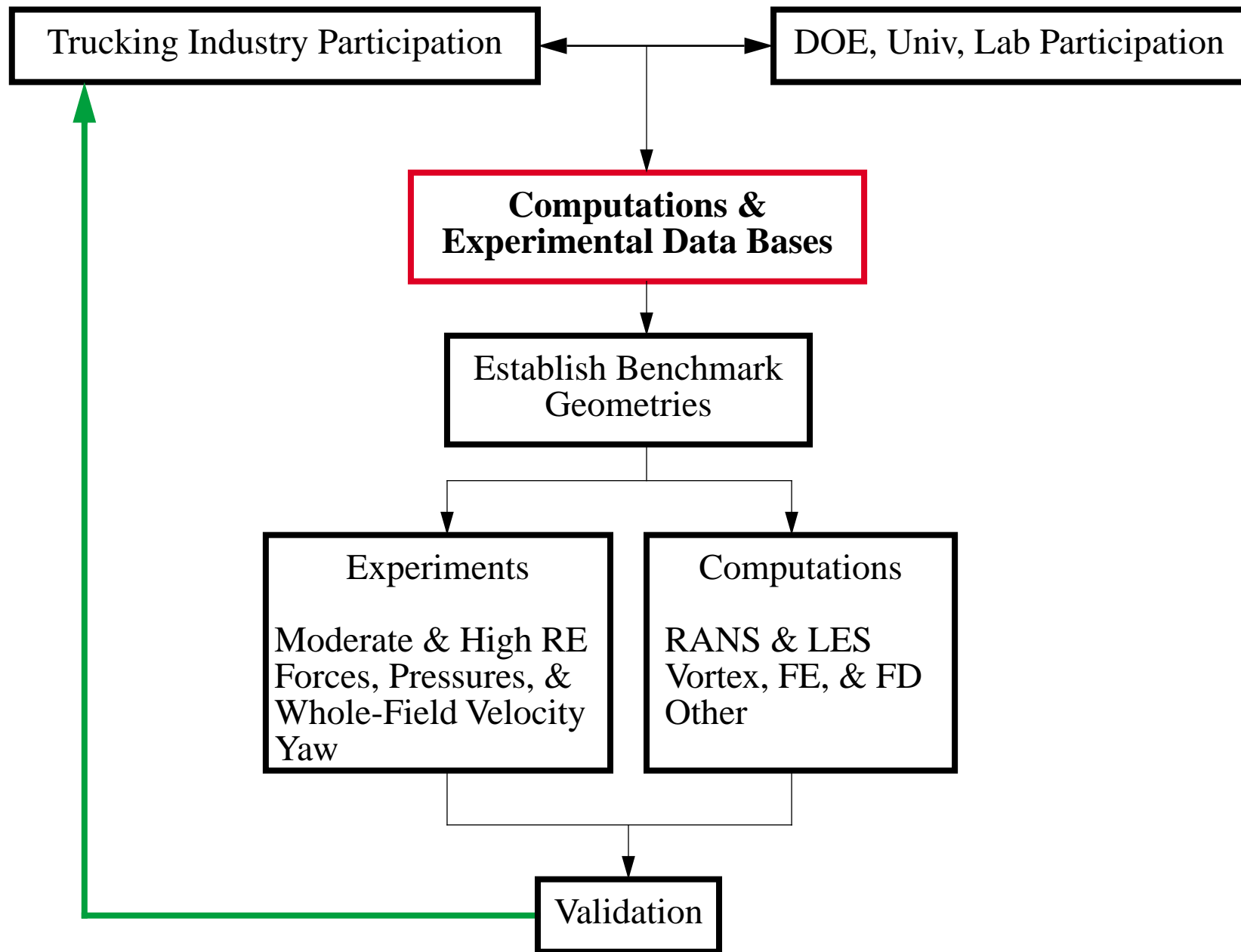
**Reynolds-averaged Navier Stokes (RANS) is common approach**

**Large-eddy simulation (LES) is in development**

**Detached-eddy simulation (DES) is in development**

**The project focus is on development and demonstration of a simulation capability.**

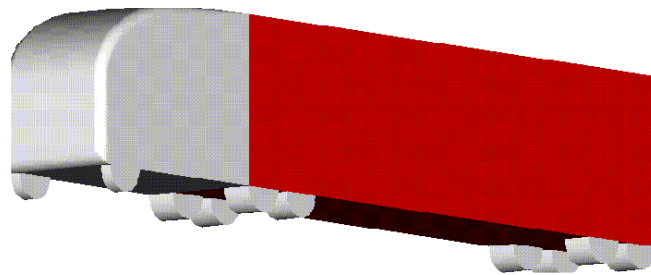
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**Near-term goal is to compare RANS and LES with experimental data for a truck problem.**

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### **Ground Transportation System (GTS)**



### **Advantages**

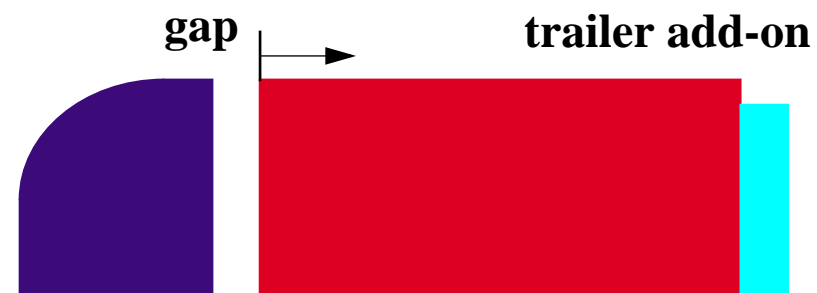
**Simple geometry**

**Some existing data**

**Some modeling already done**



**baseline GTS**



**modified GTS**

**Each organization's contributions are critical to the project's success.**

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**Experimental Modeling**

**Walt Rutledge**



GTS Experiments at  
Texas A&M

**Fred Browand  
Mustapha Hammache**



Moderate Speed  
Experiments  
in Wind Tunnel

**Jim Ross  
Bruce Storms, JT Heineck**



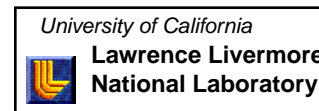
High Speed Experiments  
in 7'x10'  
Wind Tunnel

**Bob Englar**



**Computational Modeling**

**Rose McCallen (PI)**



Large-Eddy Simulation  
using  
Finite Element Methods

**Anthony Leonard  
Mark Brady**



Large-Eddy Simulation  
using  
Vortex Methods

**Kambiz Salari  
Walt Rutledge**



Reynolds-Averaged and  
Detached-Eddy Simulations  
using  
Finite Volume Methods

Active Systems

# Heavy vehicle simulations require turbulent flow approximations.

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## DNS : Direct numerical simulation

Resolution of smallest eddies - problem too big for computer

Being used for code validation with small problems

## RANS : Reynolds Averaged Navier-Stokes

Average 'steady' solution

Widely used - may not predict drag correctly

## LES : Large-eddy simulation

Unsteady solution of large scales

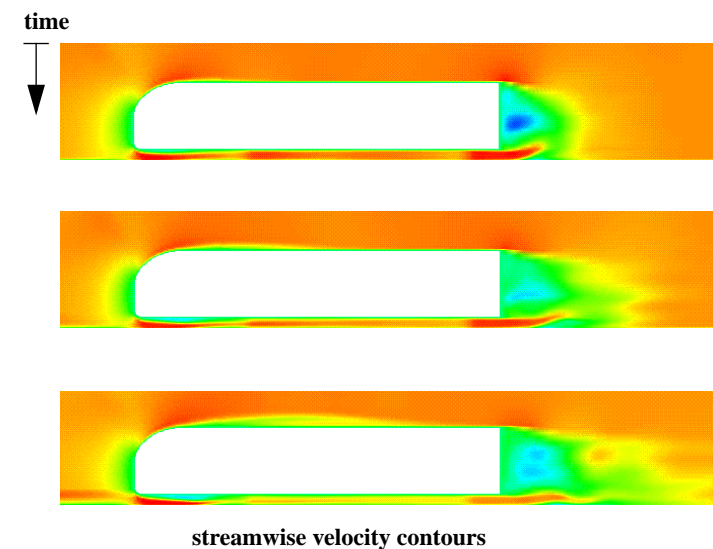
Approximation of small scales - less empiricism

Relatively new - computationally more intensive

## DES : Detached-eddy simulations

RANS near truck surface / LES away from truck surface

Very new



**Compressible as well as incompressible simulations are being performed.**

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### **Experiments**

#### **Compressible ( $Ma > 0.1$ )**

**NASA 7'x10'     $Re = 2,000,000$      $Ma = 0.27$**

**Texas A&M     $Re = 1,600,000$      $Ma \sim 0.2$**

#### **Incompressible ( $Ma < 0.1$ )**

**NASA 7'x10'     $Re \sim 740,700$      $Ma = 0.1$**

**USC     $200,000 < Re < 400,000$**

The benefits of various numerical approaches are being investigated.

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**FVM : Finite volume method**

Widely used

**FEM : Finite element method**

Widely used for solid mechanics

Used at DOE labs for multiphysics modeling

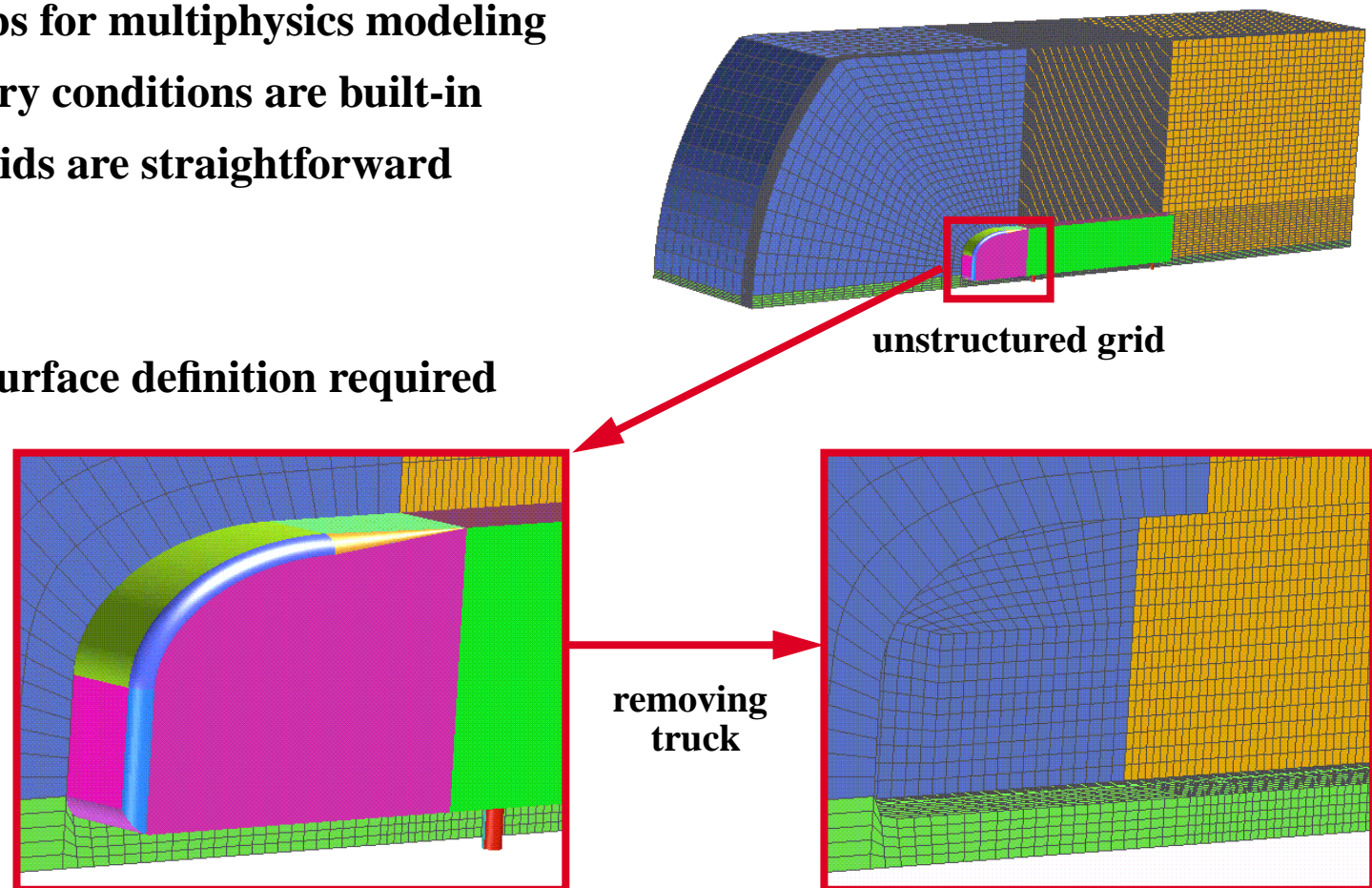
Outflow boundary conditions are built-in

Unstructured grids are straightforward

**Vortex method**

In development

Gridless - only surface definition required



# The DOE is interested in improved heavy vehicle thermal management for fuel reduction.

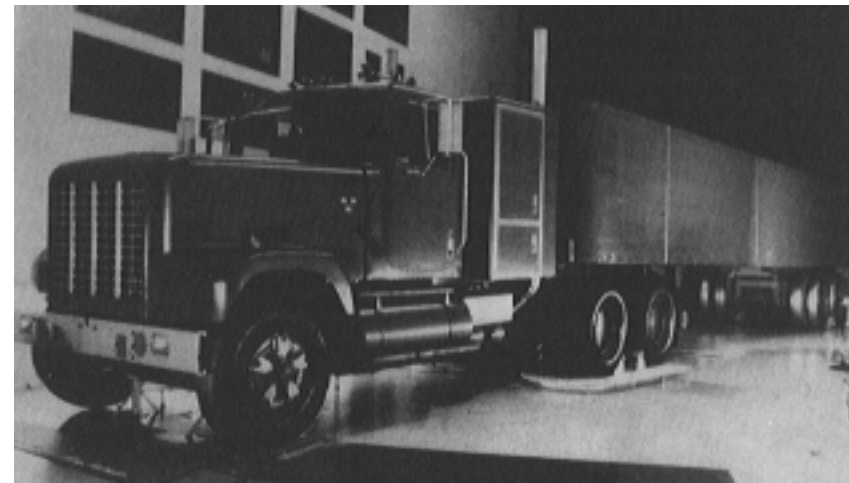
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The engine cooling airflow contributes to aerodynamic drag

1970's - 1980's Designs

$$\overline{C}_{Dtotal} = 1.0 - 0.85$$

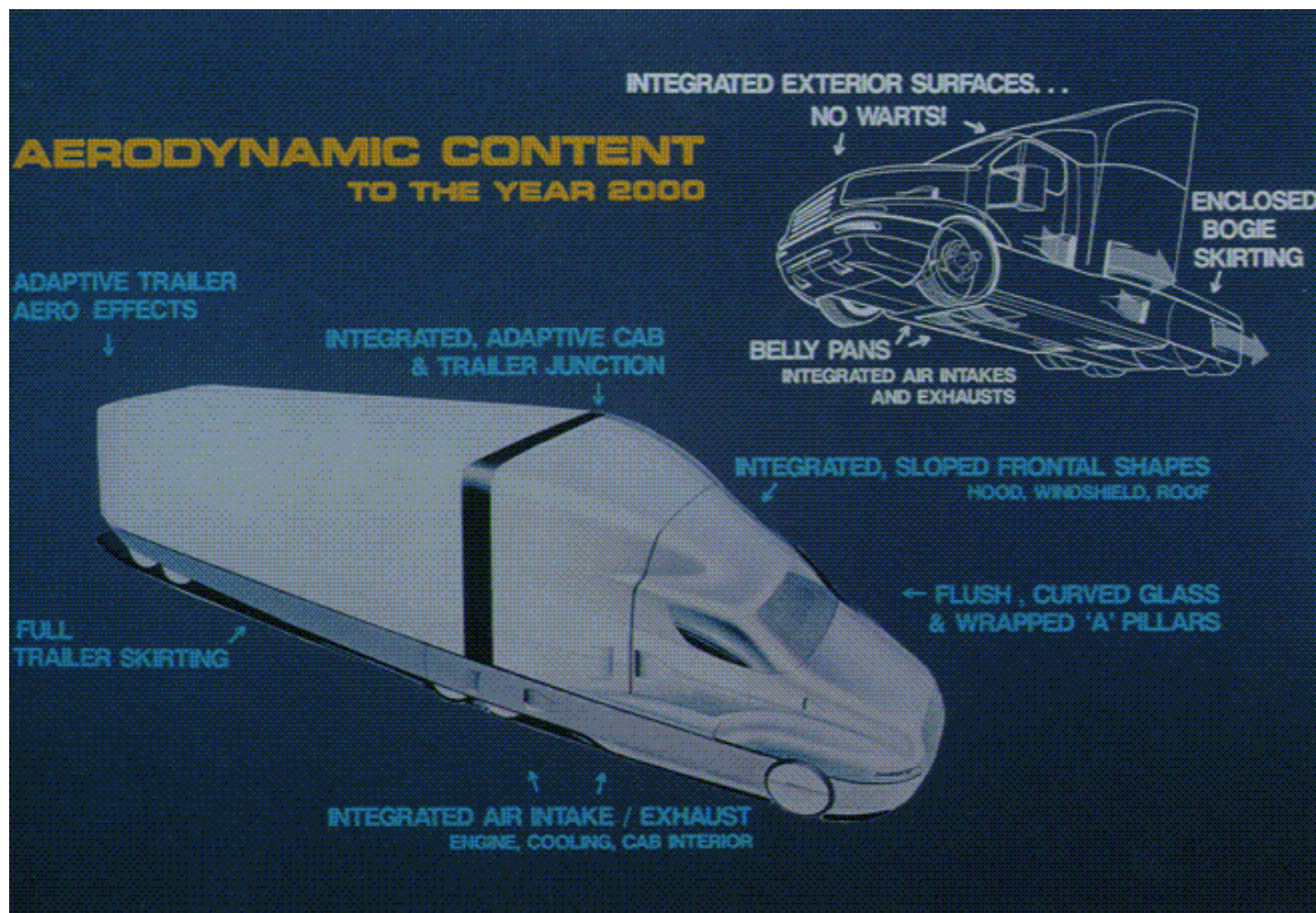
engine air cooling is 3.8% of  $\overline{C}_{Dtotal}$



Ref. Olson and Schaub, 1992, SAE 920345

The designs of tomorrow will be integrated and emphasize internal and external flow management.

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Navistar International Transportation Corp.

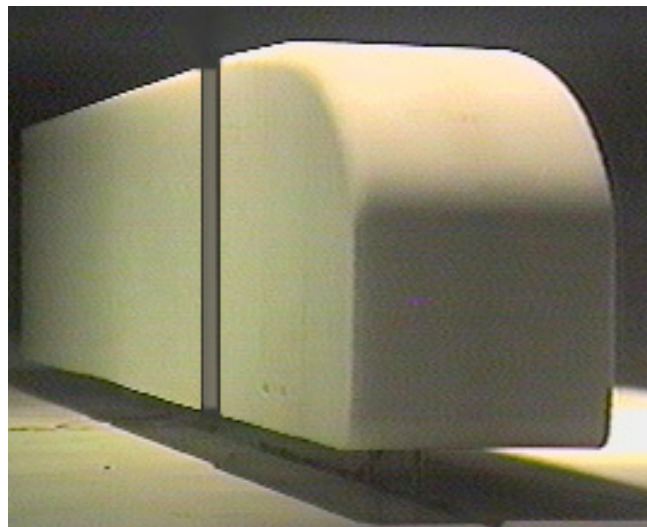
# **Tractor-Trailer Gap: The Relationship Between Measured Drag and Measured Flow Field**

**M. Hammache  
F. Browand**



**Ground Vehicle  
Aerodynamics Lab**

M. Michaelian, staff  
G. Landreth, student  
D. Lazzara, student  
R. Blackwelder, staff  
P. Lissaman, staff  
D. Schwamborn, visiting scientist  
(DLR-Gottingen, Germany)



Rapid prototype from dense Styrofoam

- 1/14 scale models
- Variable gap between tractor and trailer
- Measure drag and side force on cab and trailer separately

Dryden wind tunnel at USC

- Top speed of 70 mph
- Reynolds number,  $Re = UL/\nu = 100,000-350,000$   
based upon  $L =$  Frontal Area

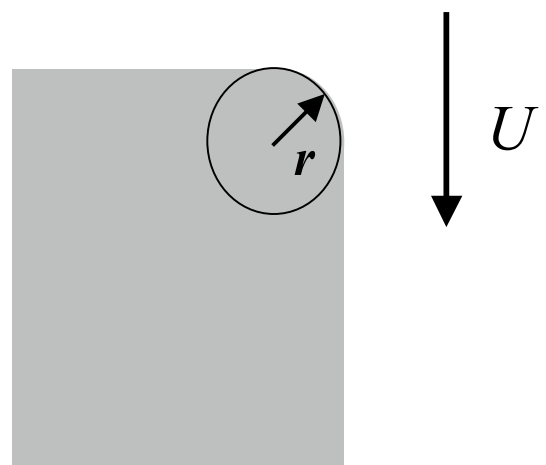
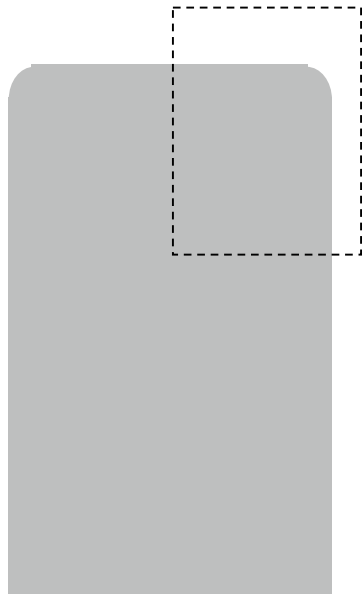
# Wind Tunnel Measurements

Tractor and trailer drag measured separately, illustrating

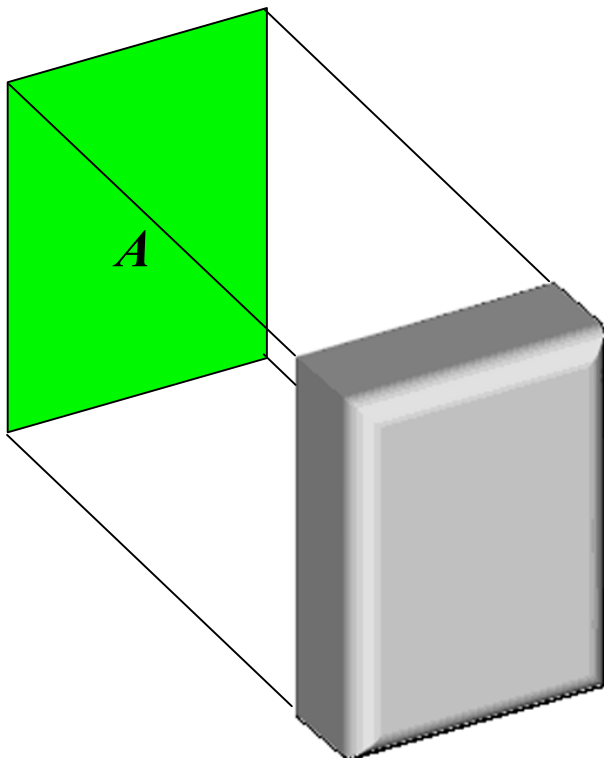
importance of tractor leading edge radius  
variation of drag with gap length

Employ DPIV (Digital Particle Image  
Velocimetry) to observe flow field within  
the gap

## Reynolds number scaling



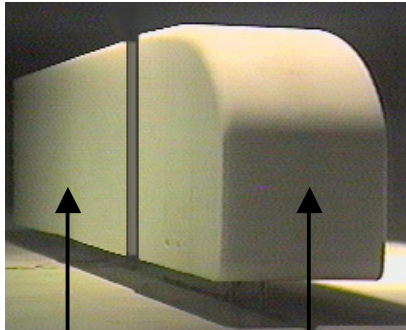
$$\text{Re} = \frac{Ur}{\nu}$$



$$\text{Re} = \frac{UL}{\nu}$$

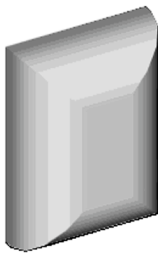
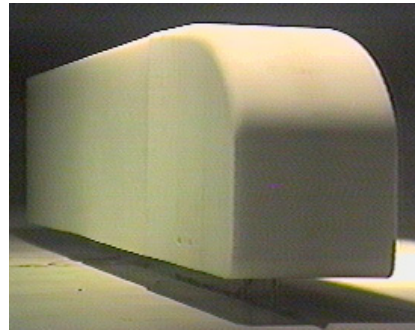
where  $L = \sqrt{A}$

# The Ground Transport Vehicle (GTS)



Trailer

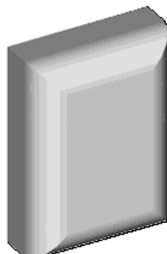
Cab



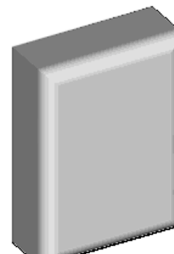
**R 2.5"**



**R 2.0"  
w/ Sandpaper**



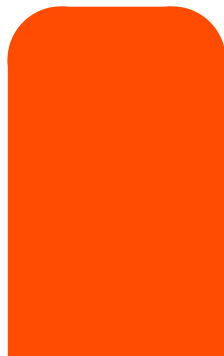
**R 1.5"**



**R 0.75"**



**R 0.5"**



GTS cab with  
R = 2"  
(Top view)



Original  
GTS cab  
(Top view)

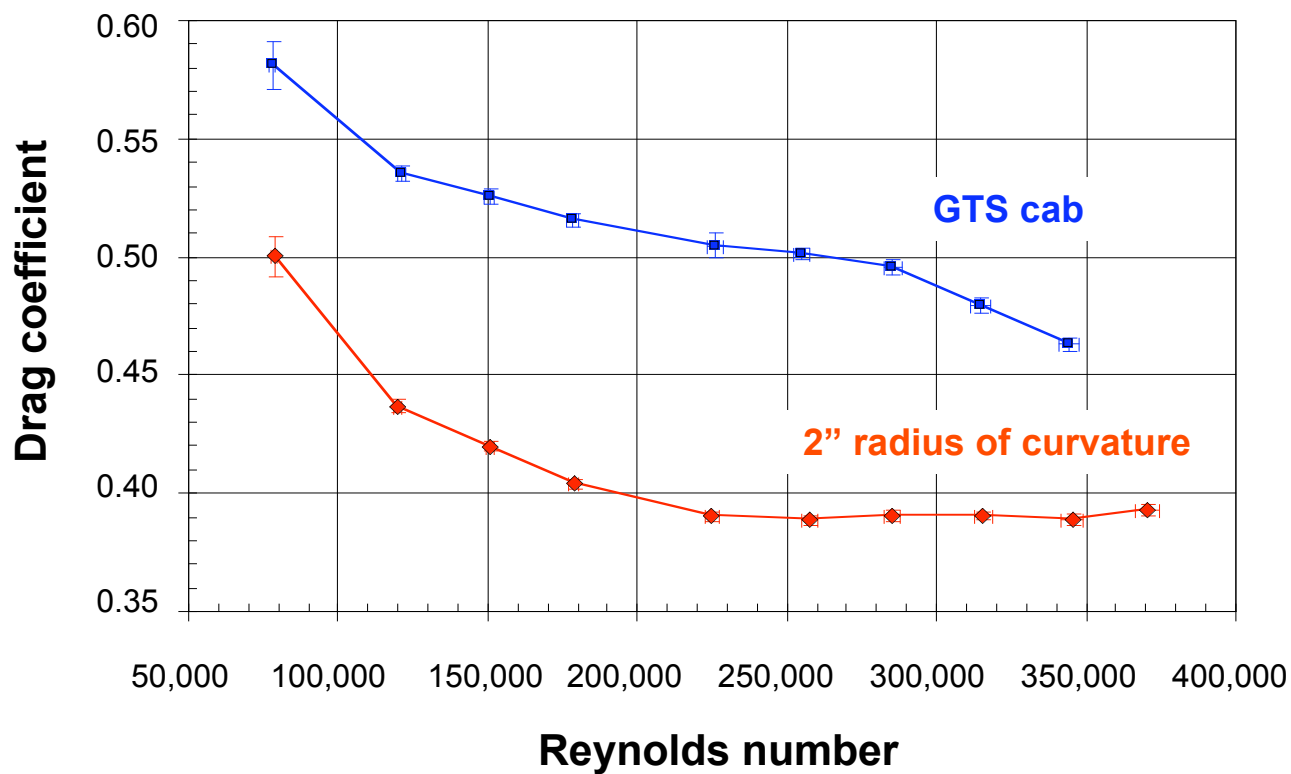


GTS cab with  
R = 2"  
(Top view)



Original  
GTS cab  
(Top view)

### Drag coefficient of isolated cab



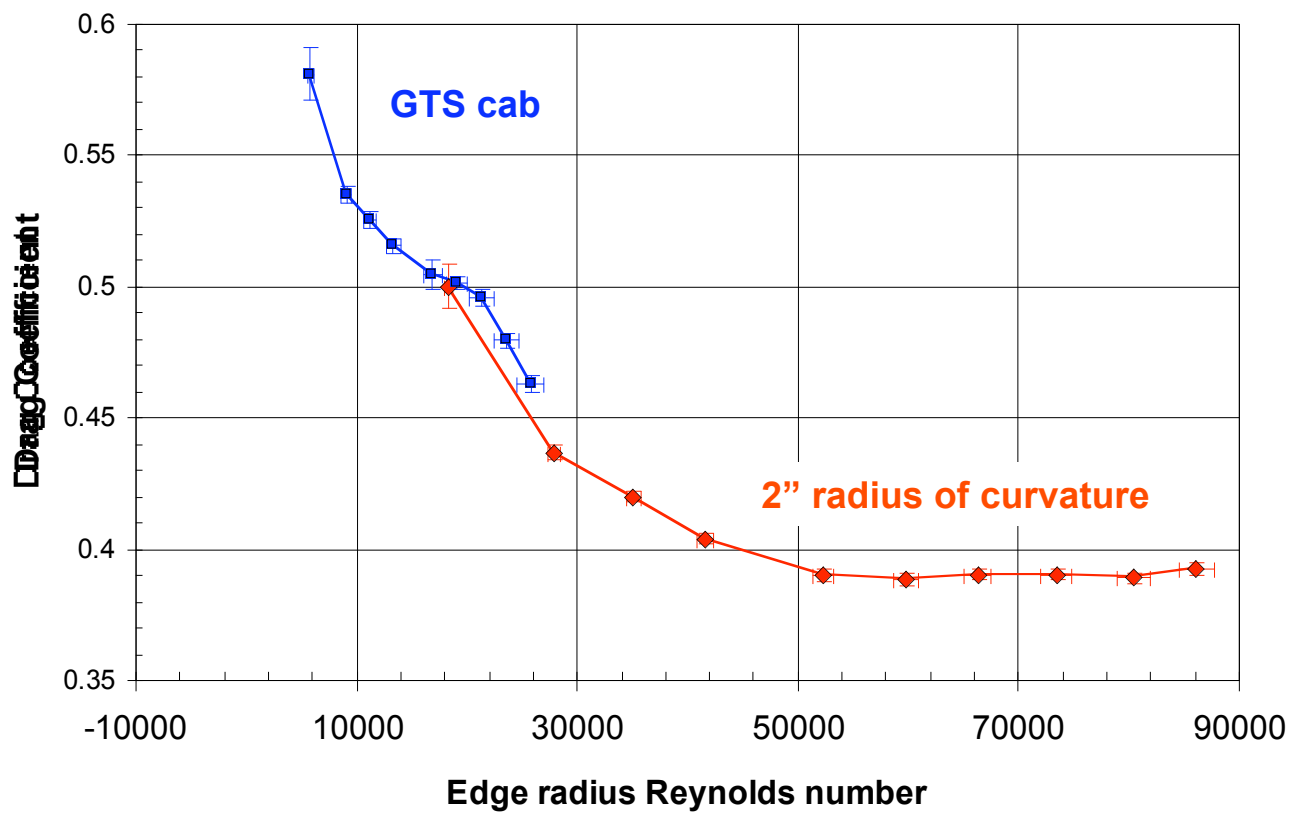
$$Re = \frac{U \sqrt{A}}{\mu}$$



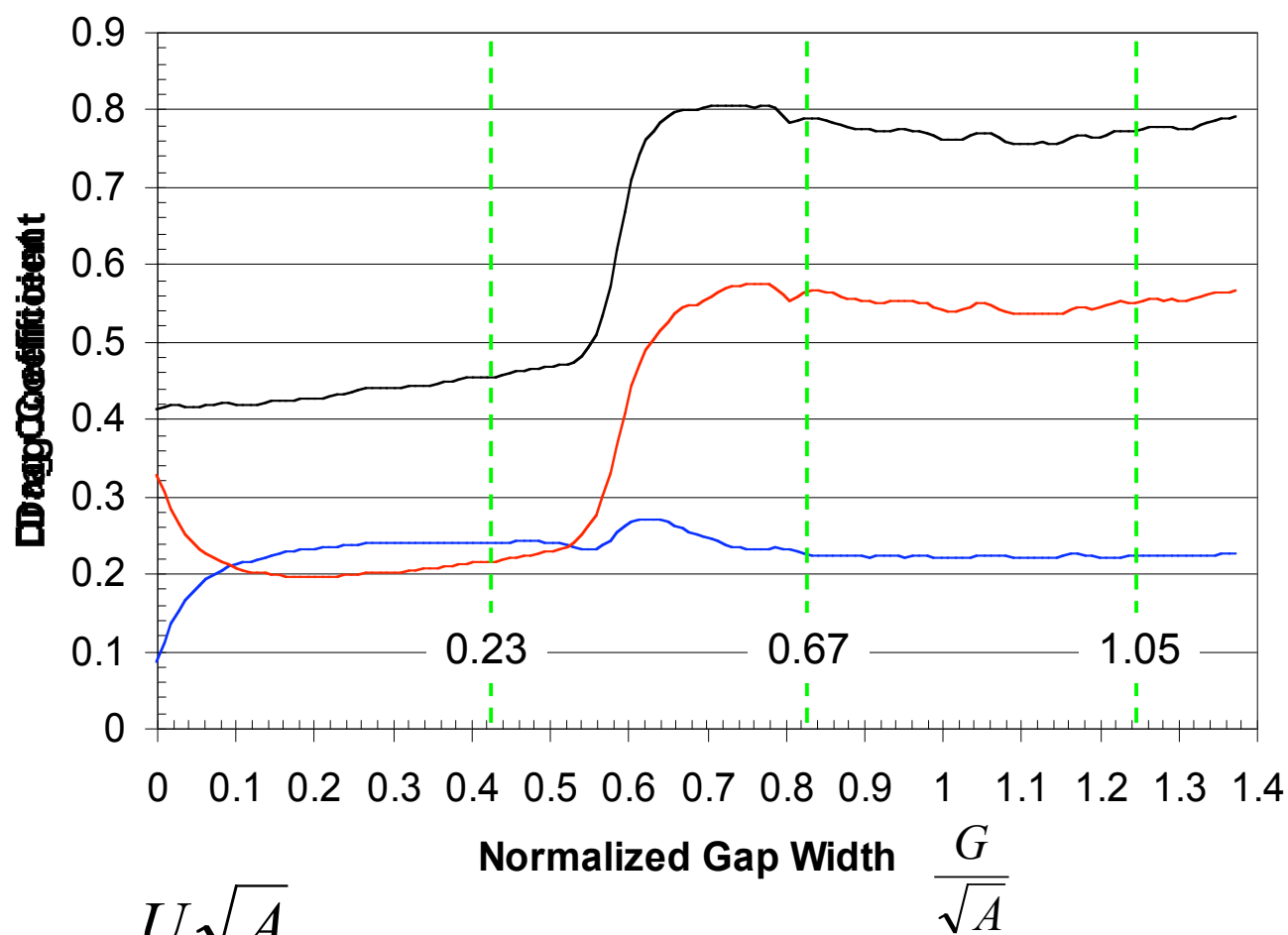
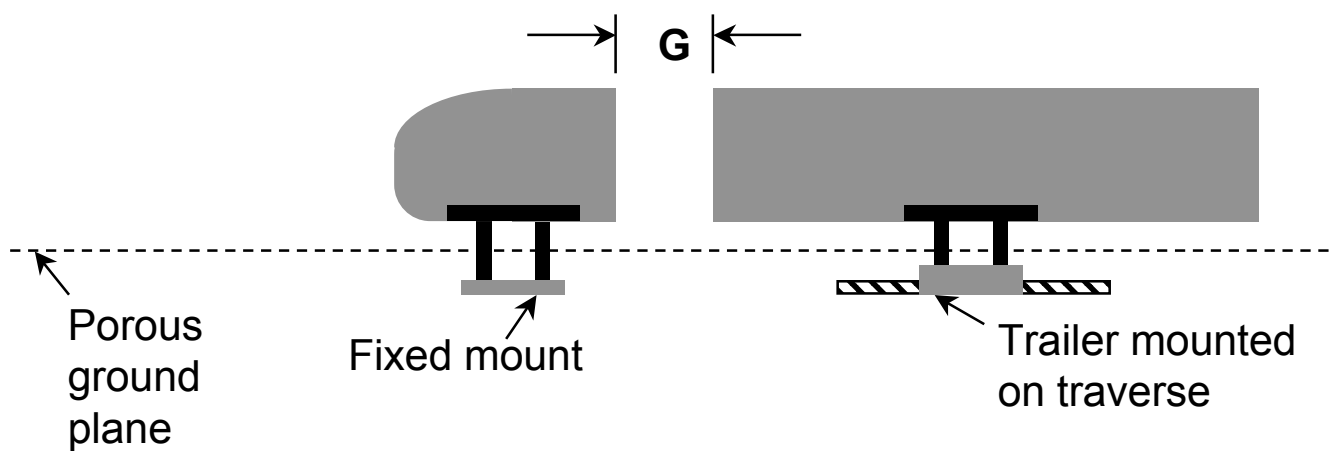
GTS cab with  
R = 2"  
(Top view)



Original  
GTS cab  
(Top view)



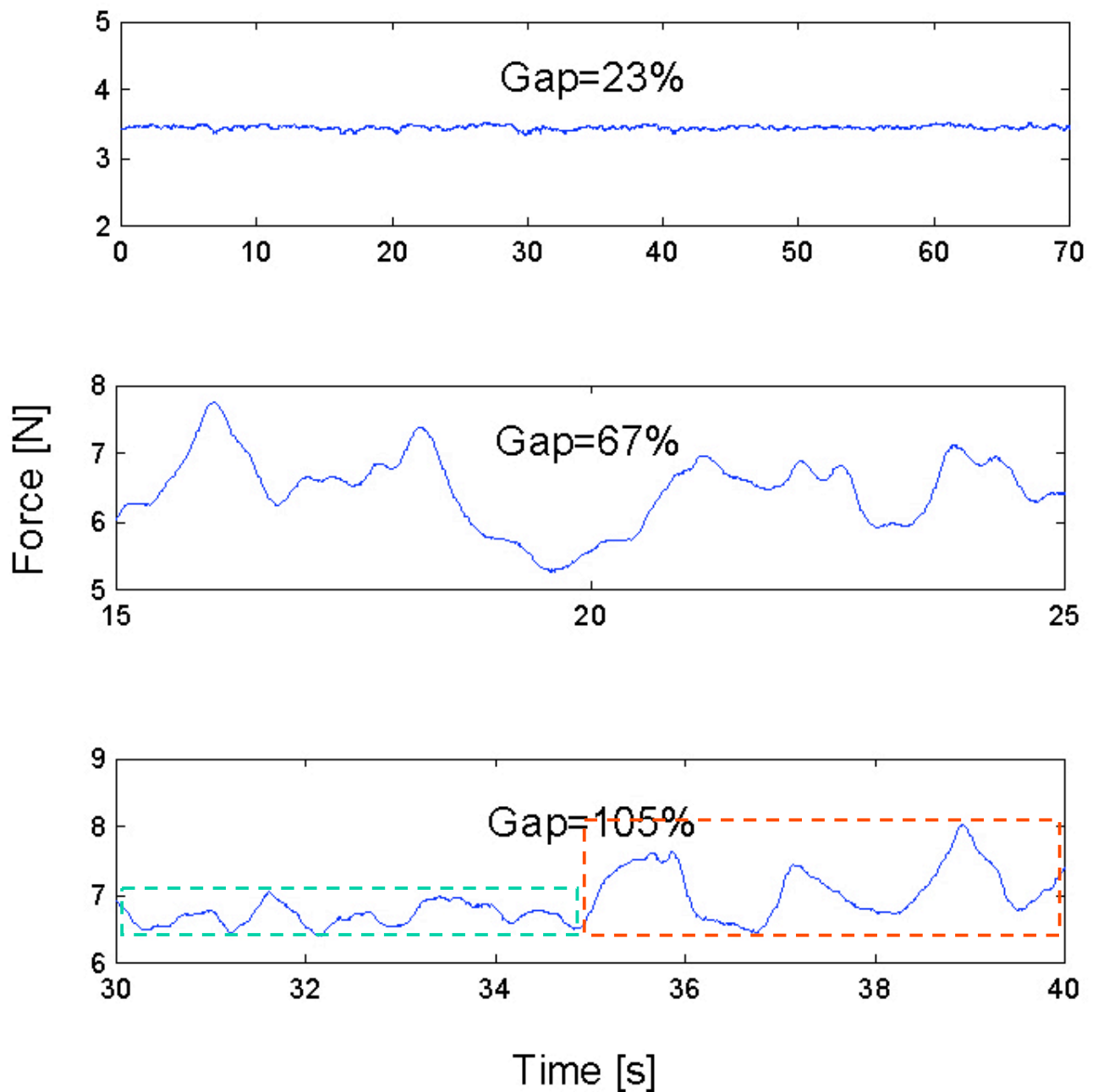
$$Re = \frac{Ur}{\nu}$$

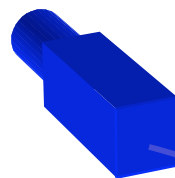
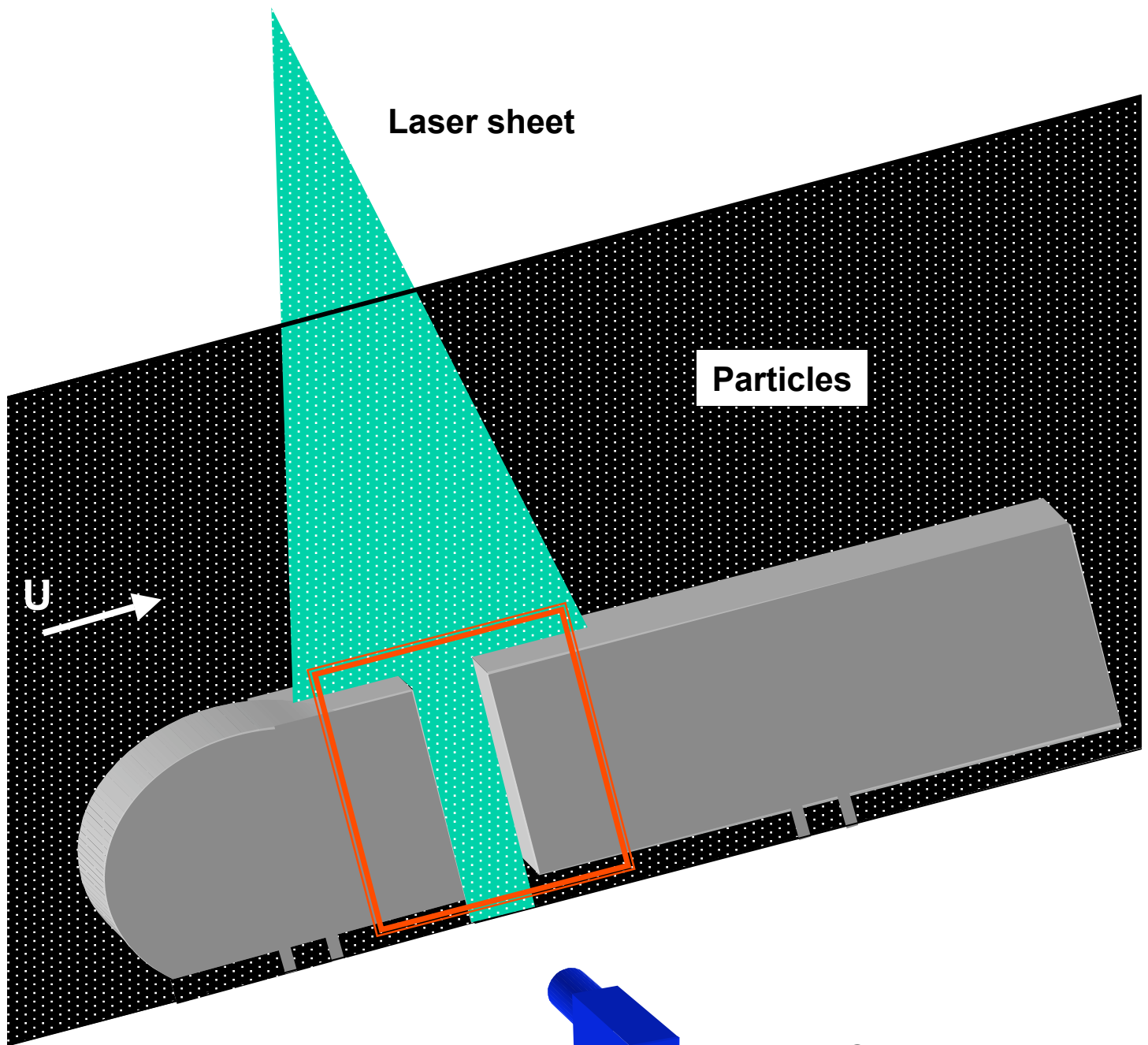


$$\text{Re} = \frac{U \sqrt{A}}{\nu} = 330,000$$

## Time signature of drag force on trailer as a function of gap size

$Re=305,000$



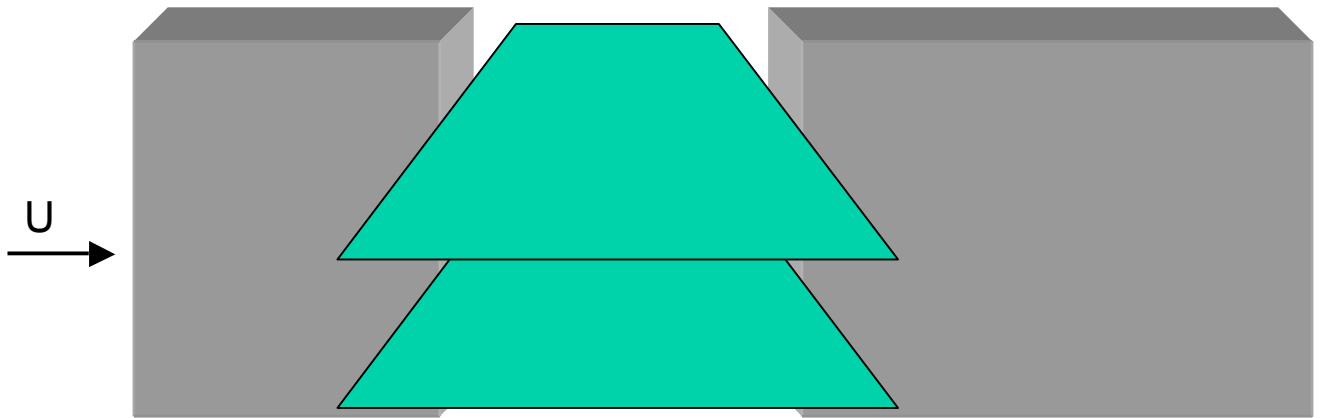


CCD camera

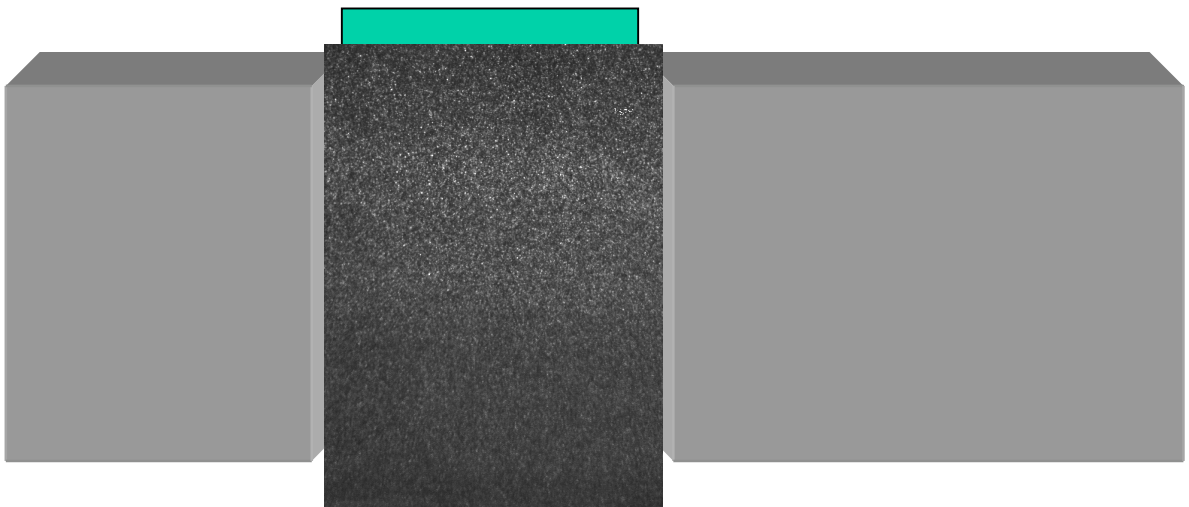
PC with  
digitizer board



Digital  
Particle  
Image  
Velocimetry



**Horizontal planes**



**Vertical planes**

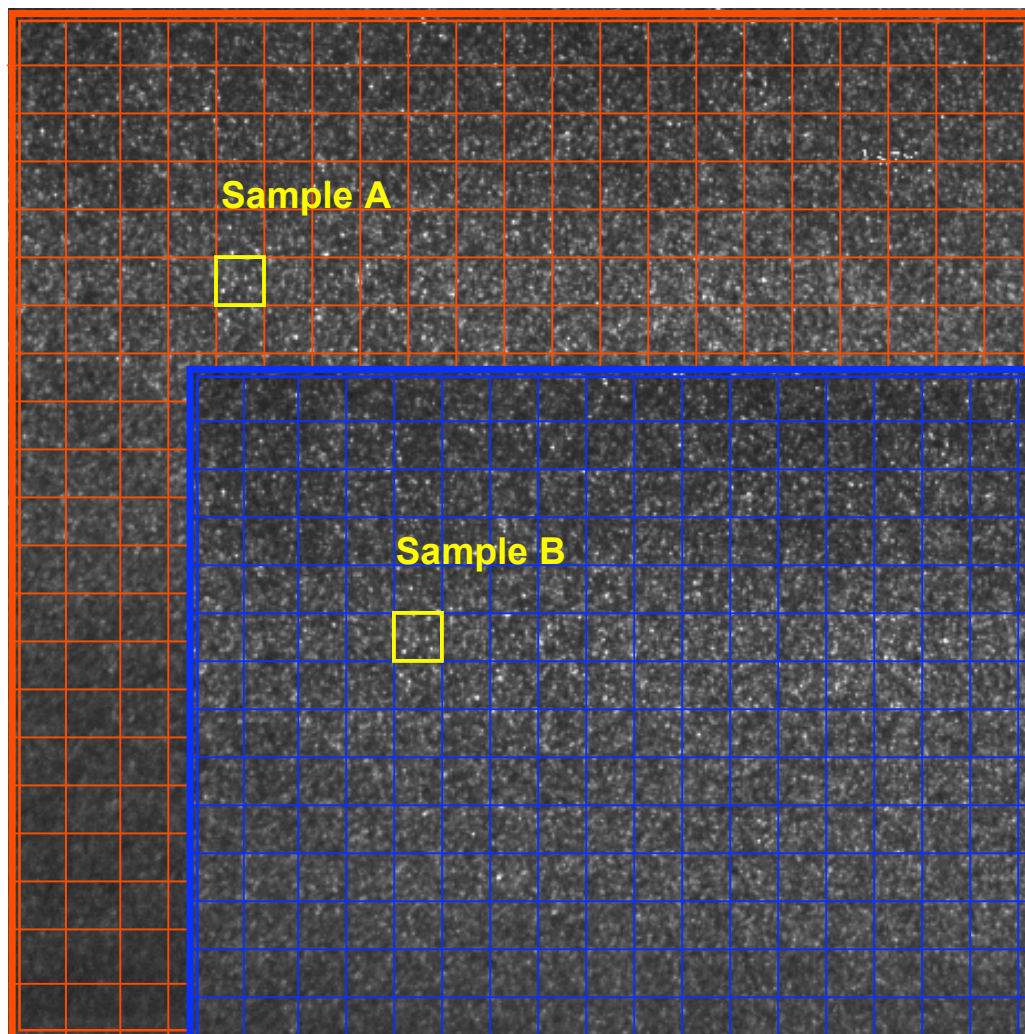


Image A  
at time  $t_1$

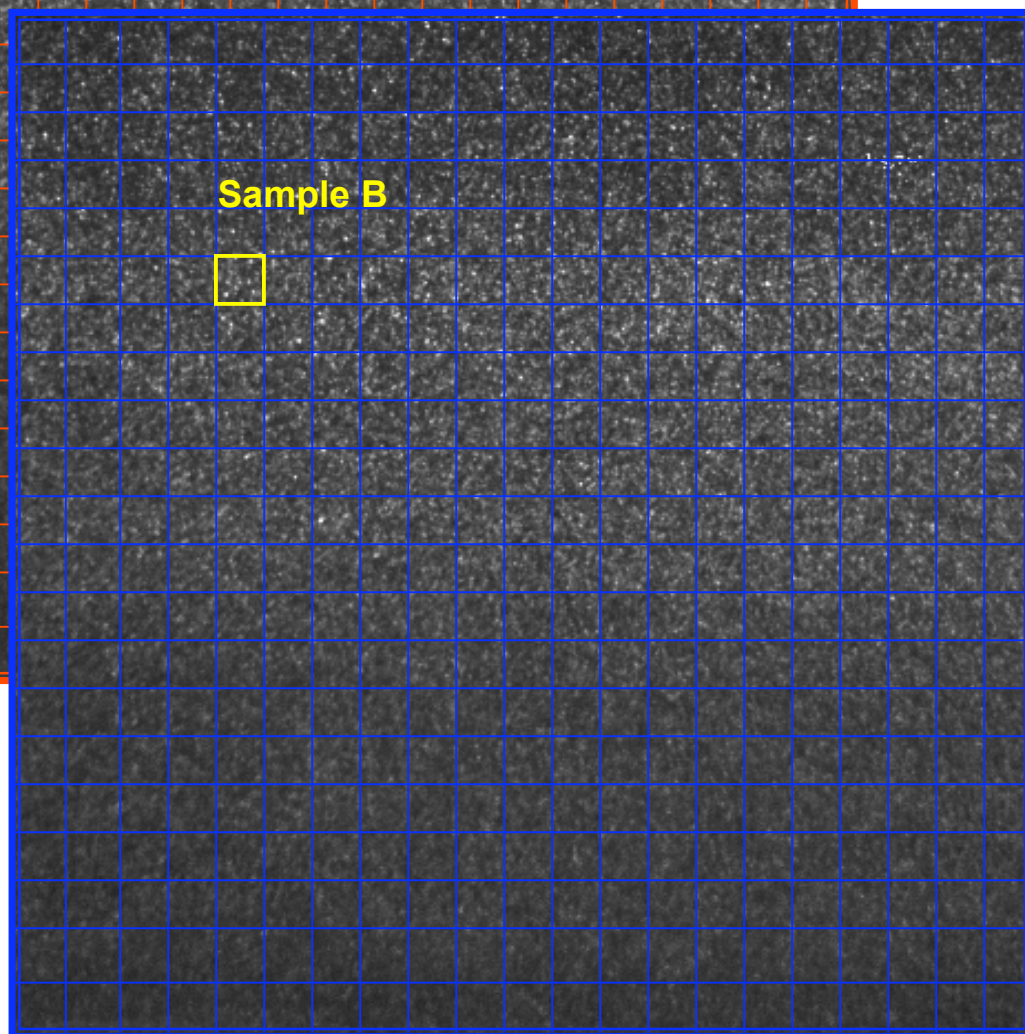
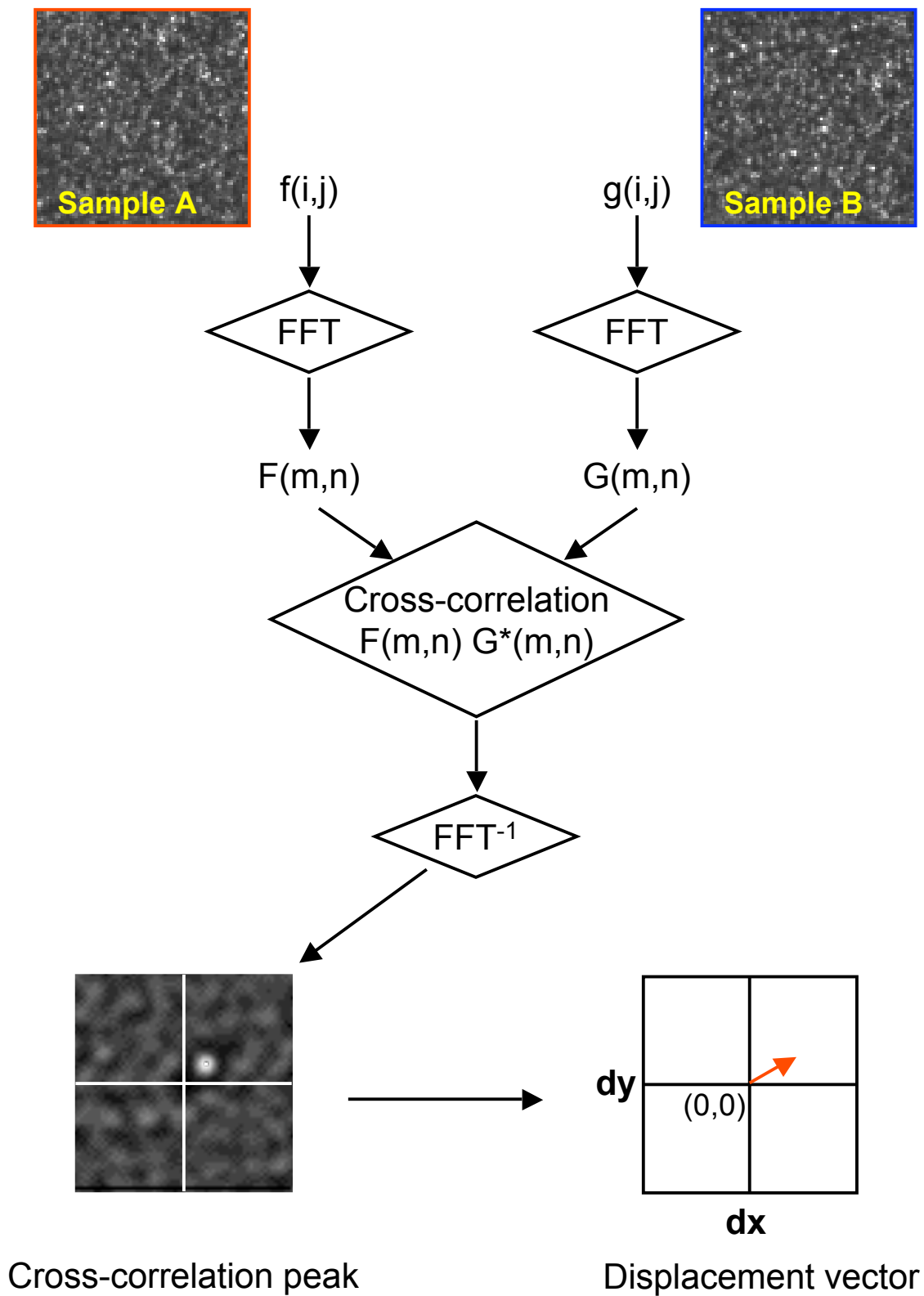


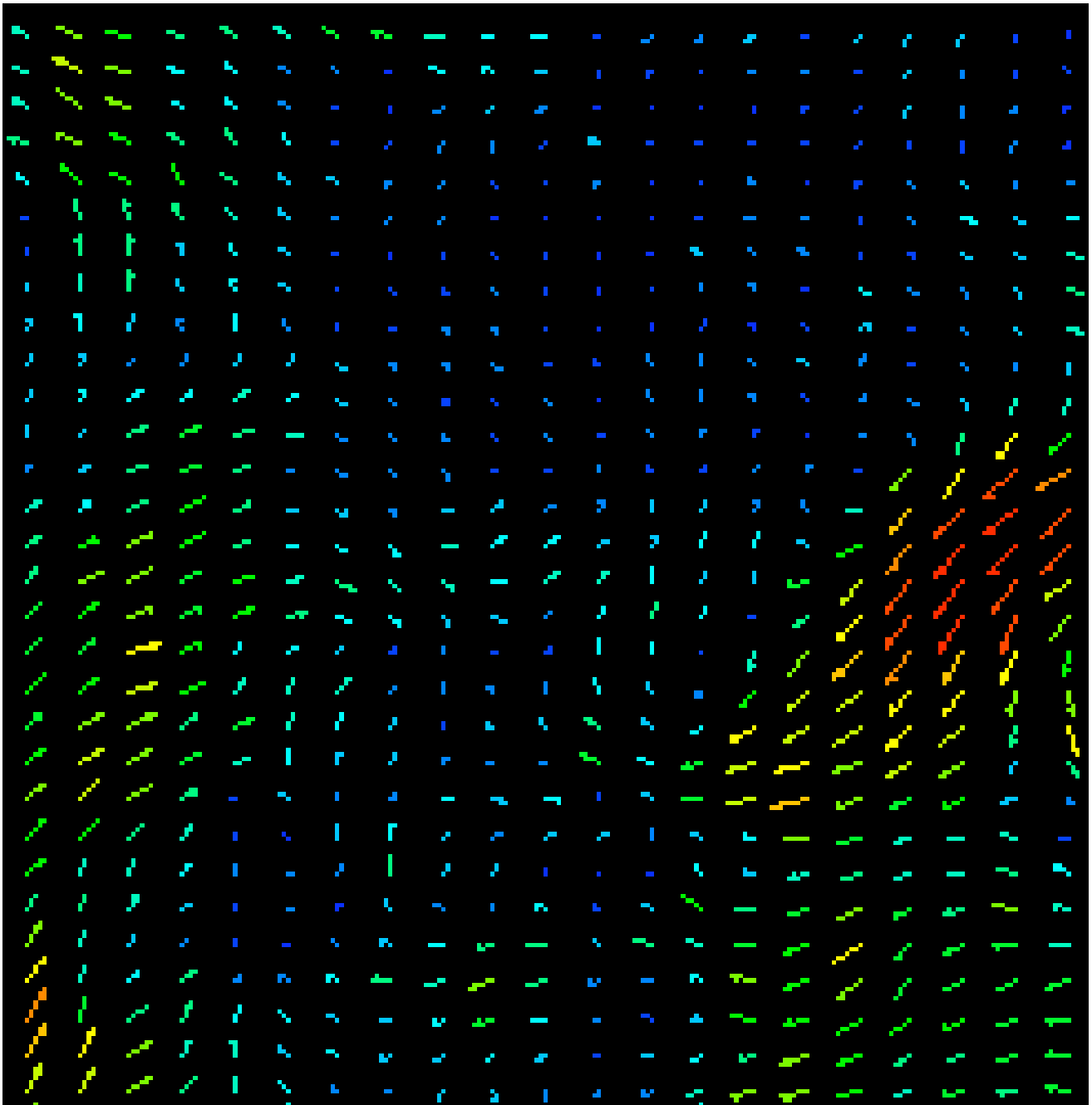
Image B  
at time  $t_2=t_1+dt$

$dt \sim \text{microseconds}$

# DPIV processing with the cross-correlation technique

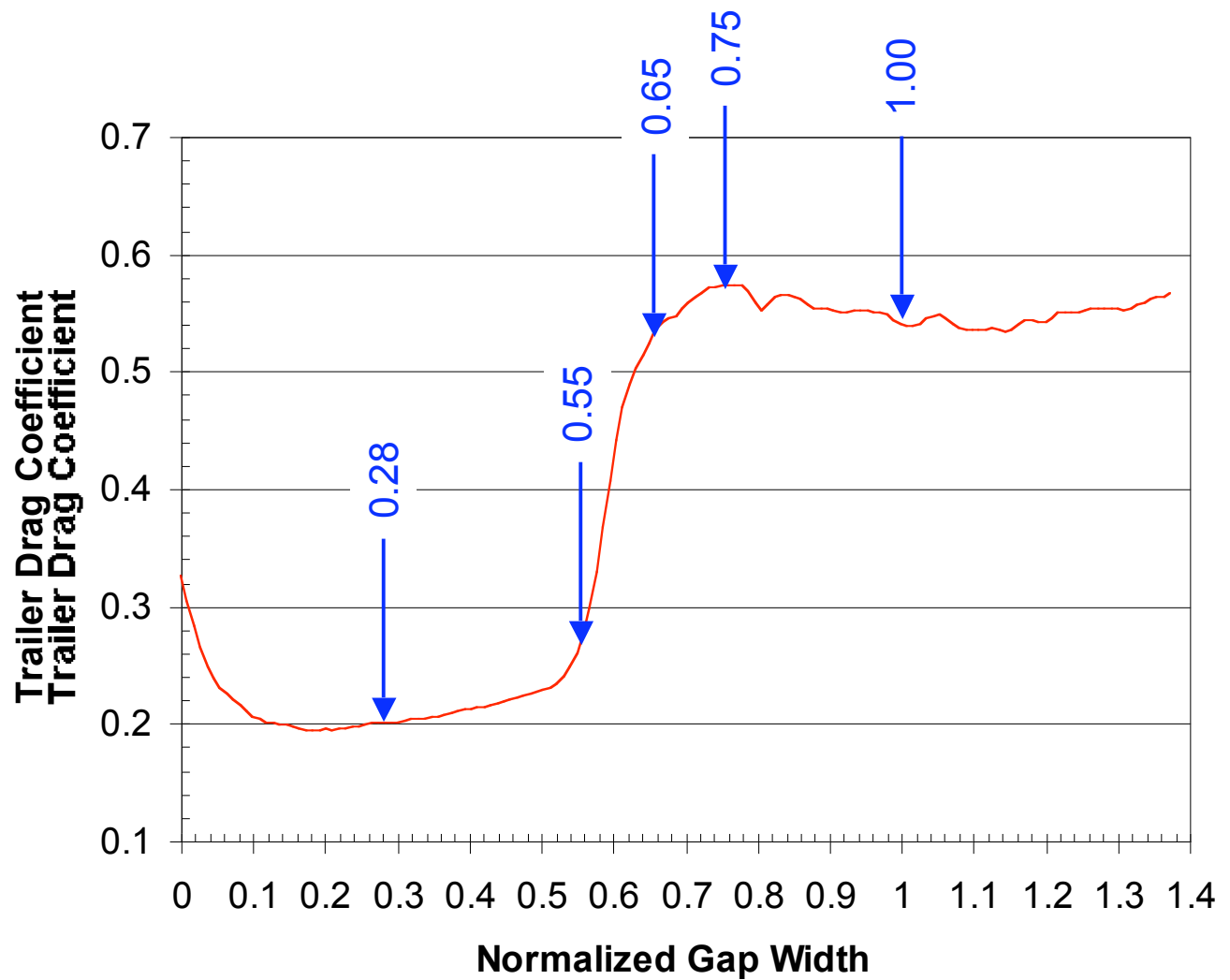


## Reconstructing the two-dimensional displacement field



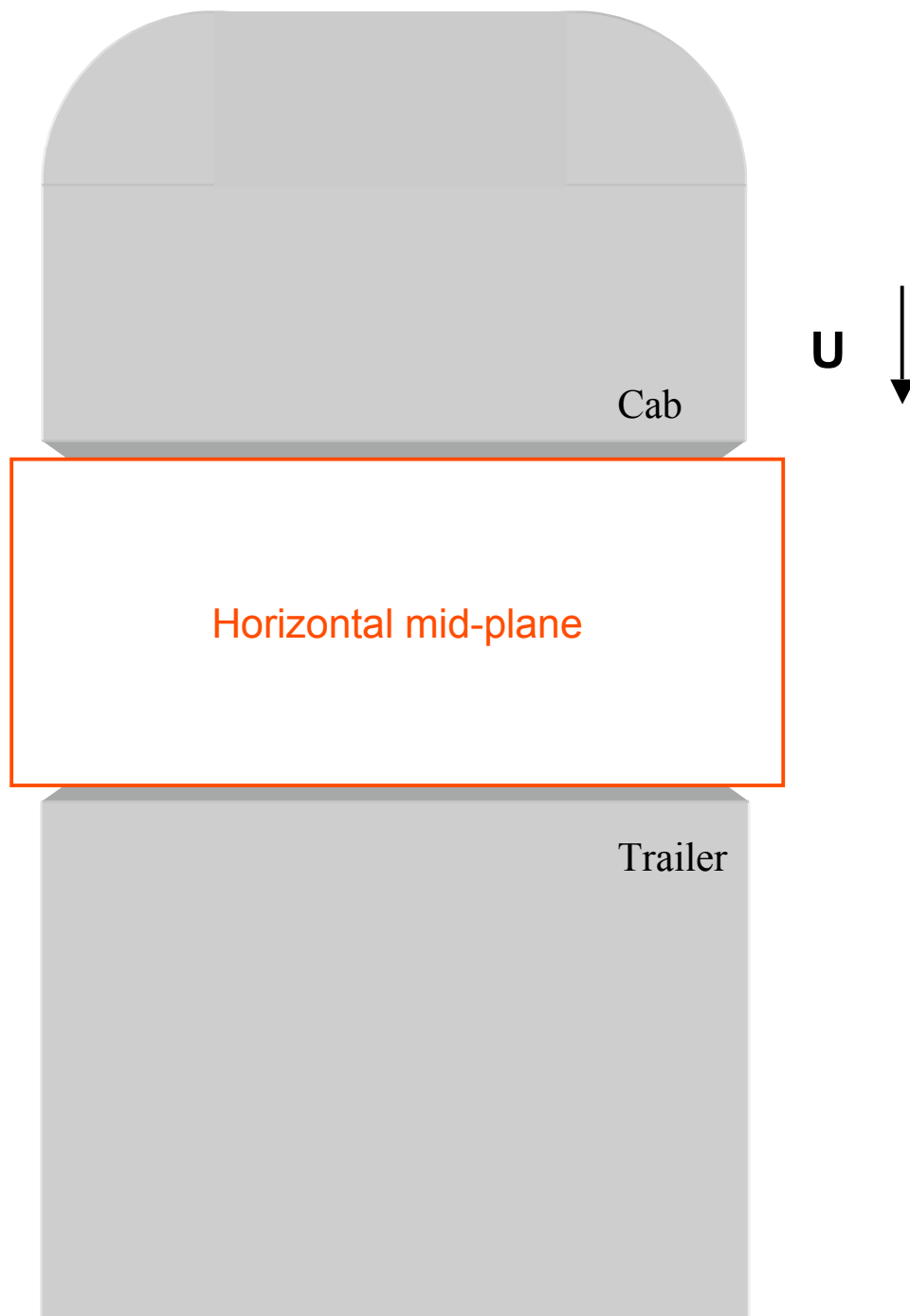
$$\text{Velocity field} = (\text{Displacement field}) / dt$$

# DPIV test conditions

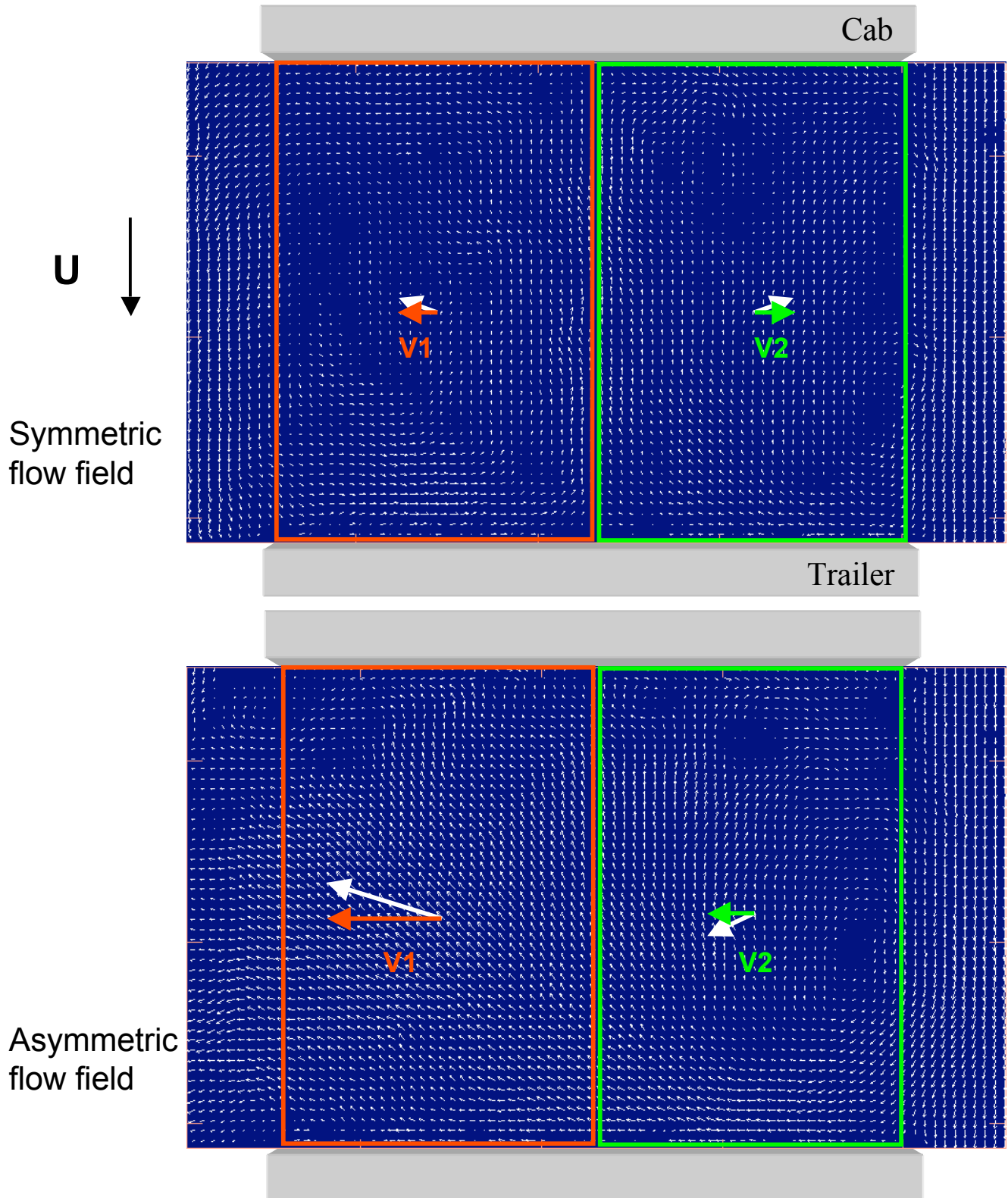


**Re=330,000**

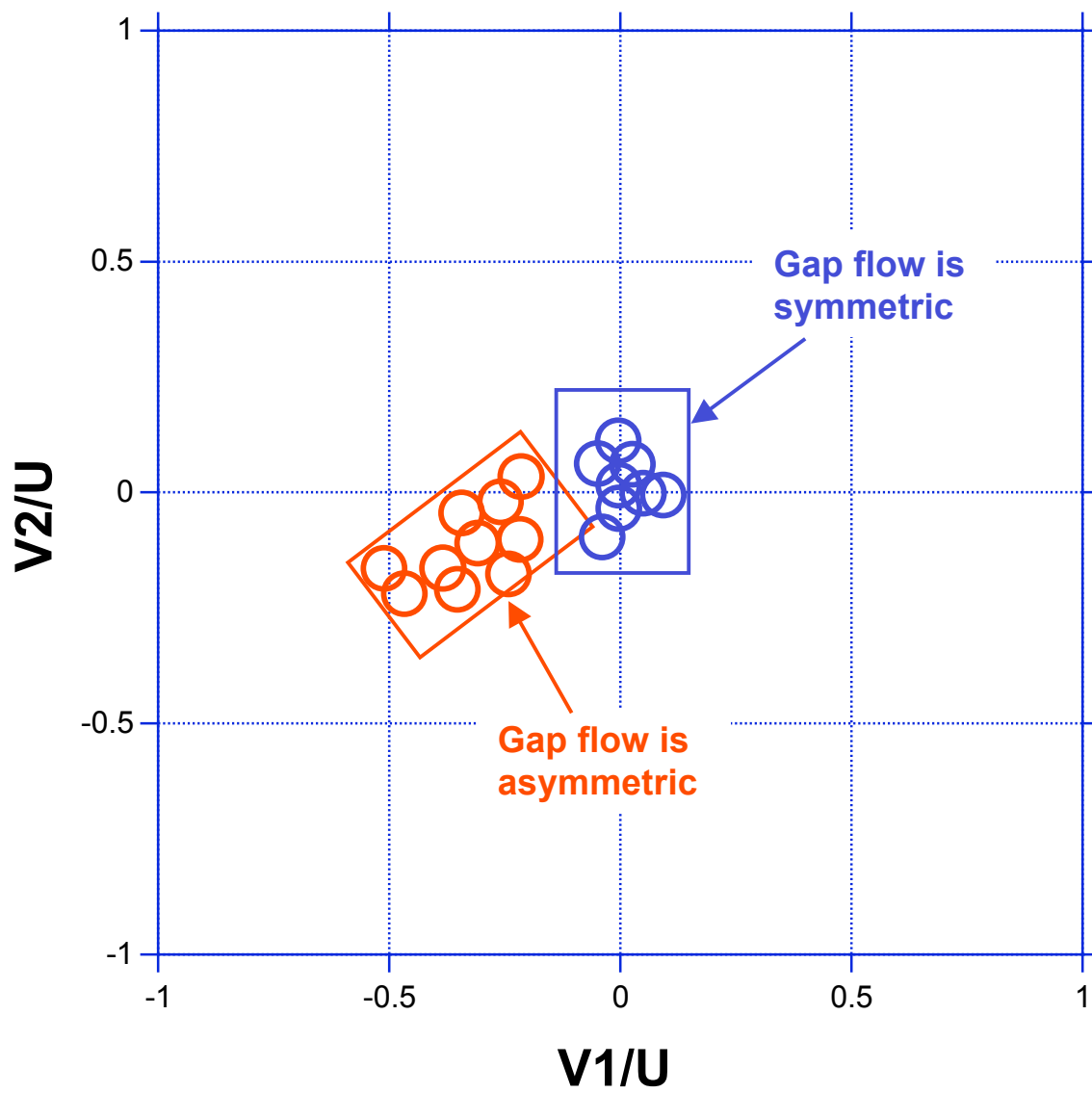
## DPIV measurements in horizontal mid-plane



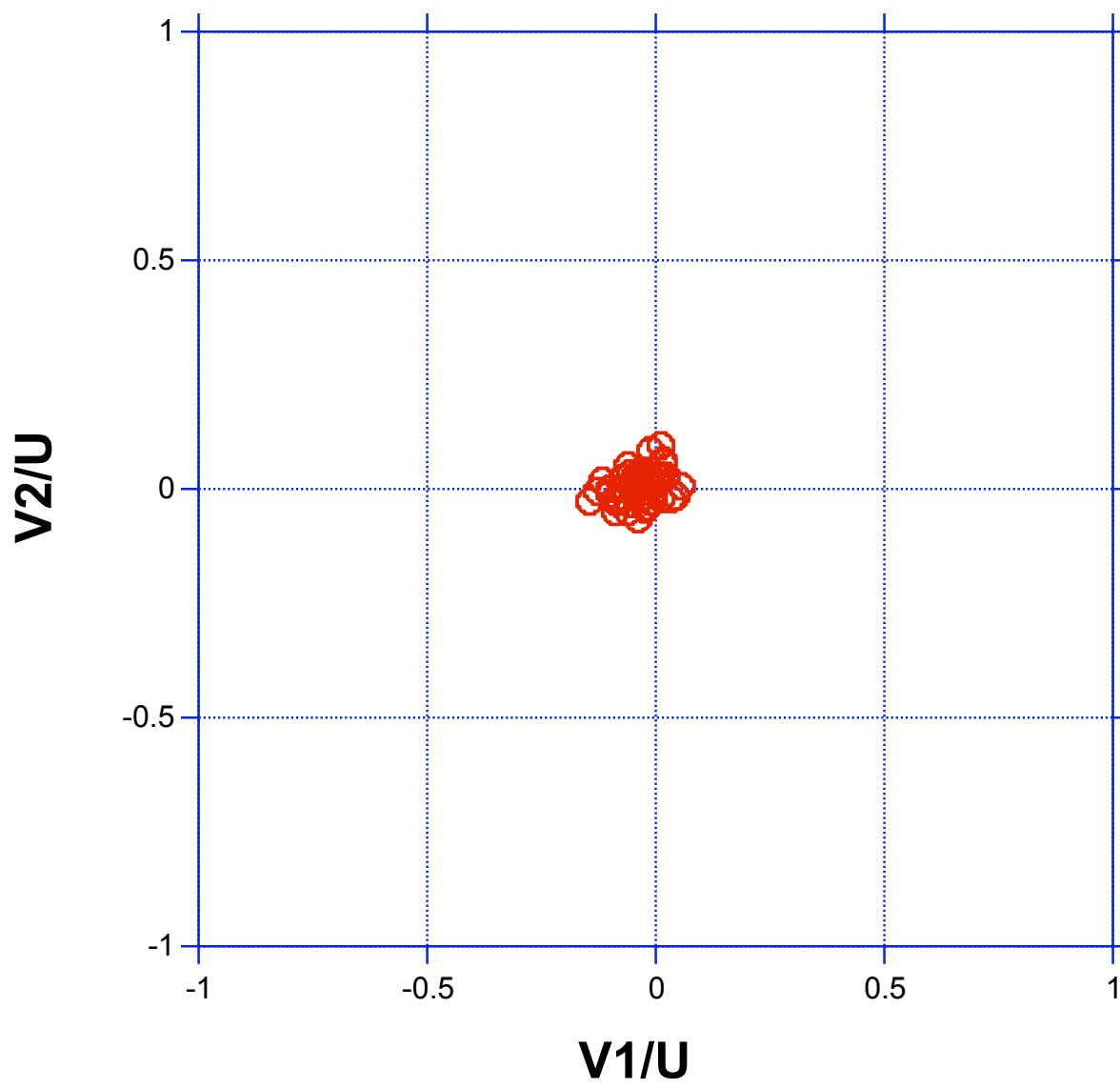
# Instantaneous velocity vector fields



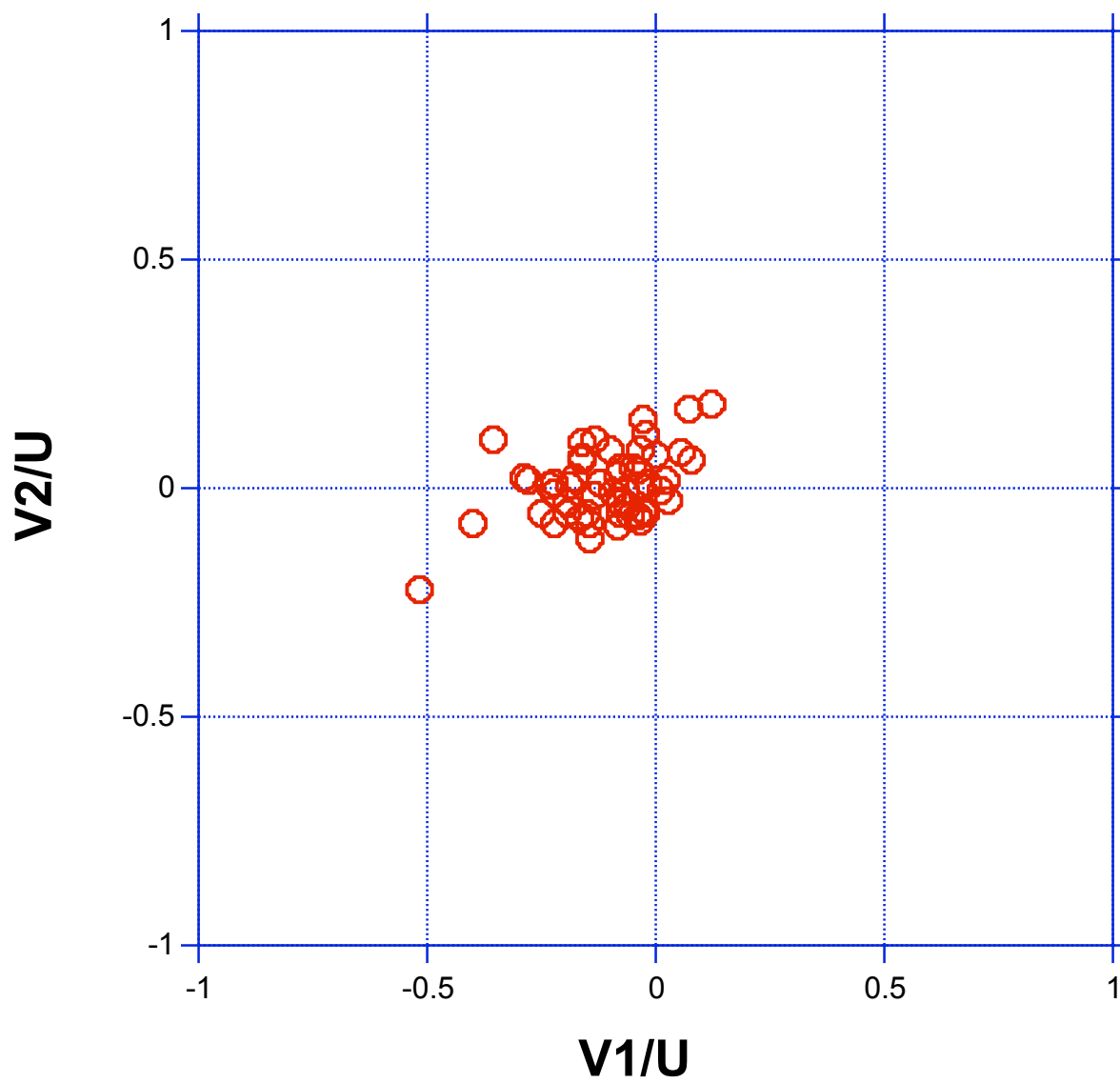
**(V1, V2) define a state space**



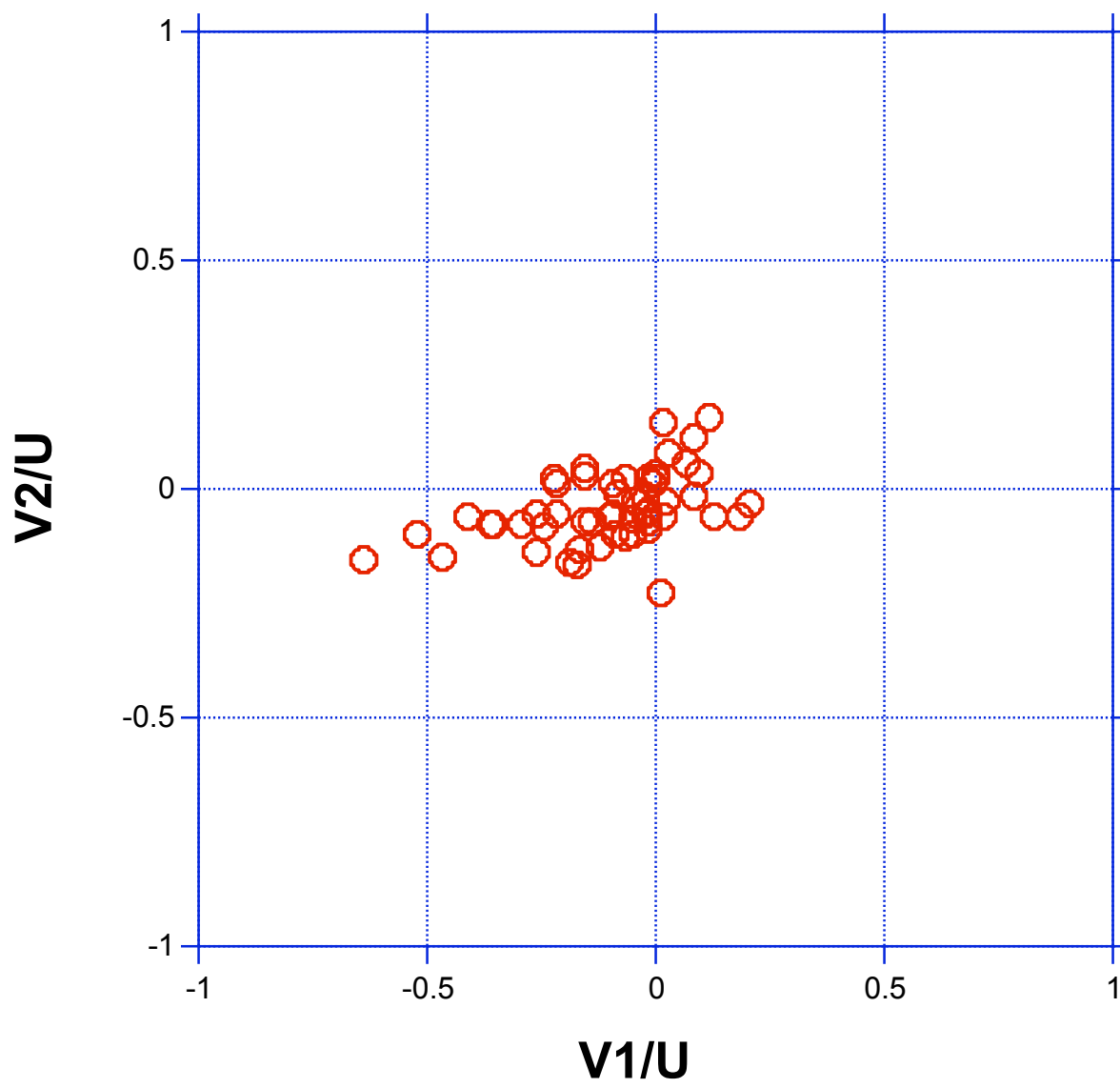
$$G/L = 28\%$$



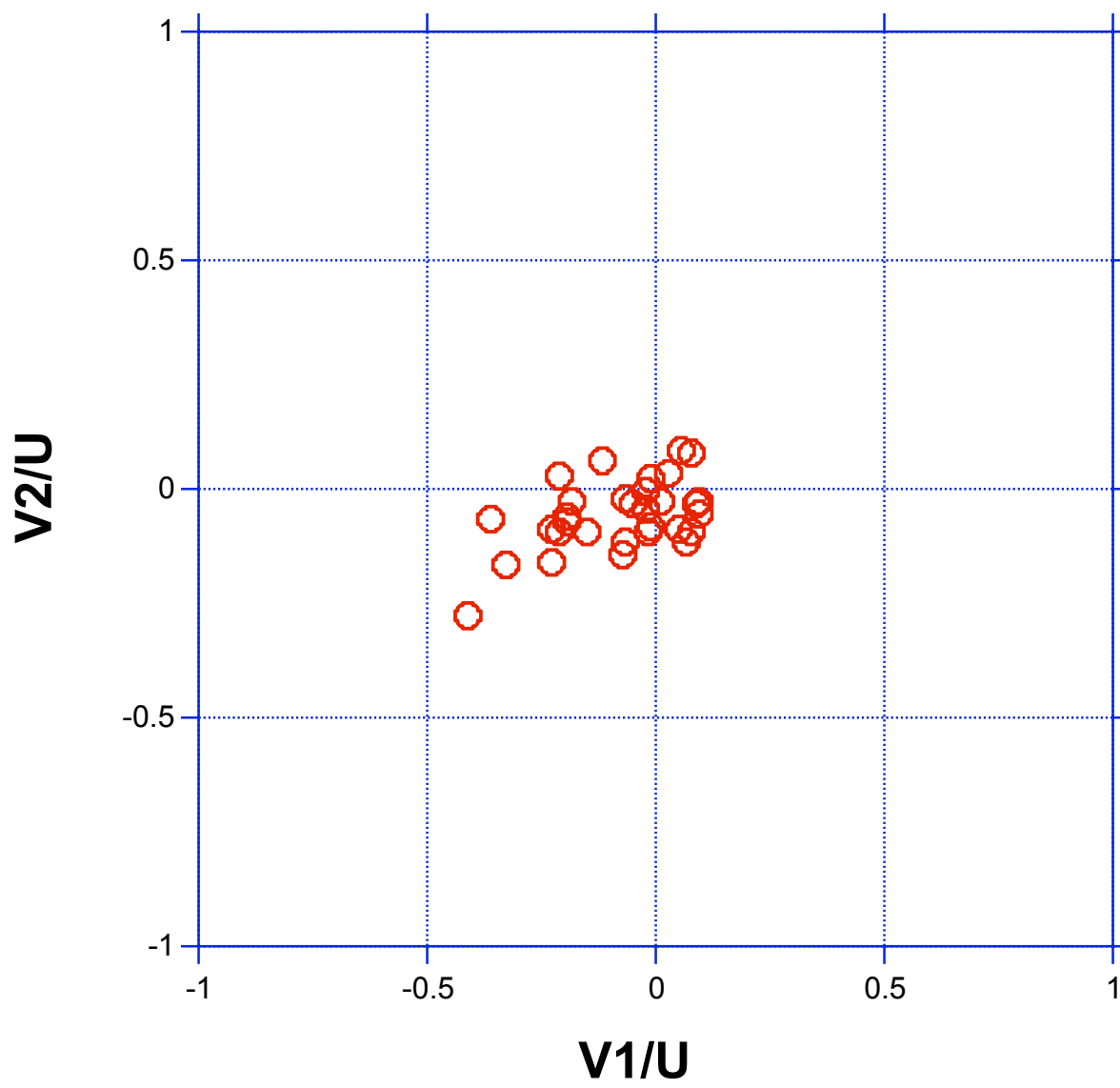
**$G/L = 55\%$**



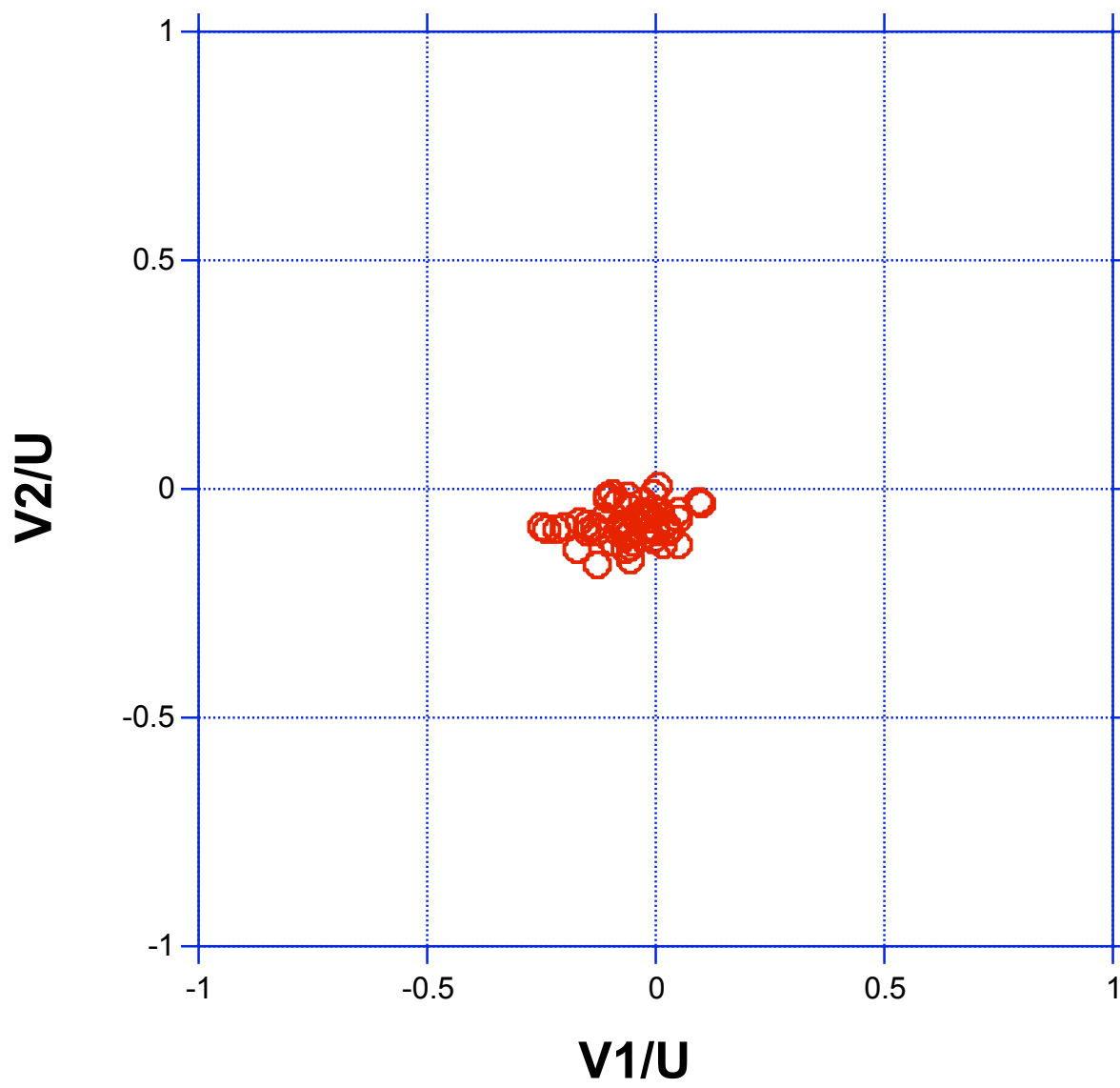
**$G/L = 65\%$**



**$G/L = 75\%$**

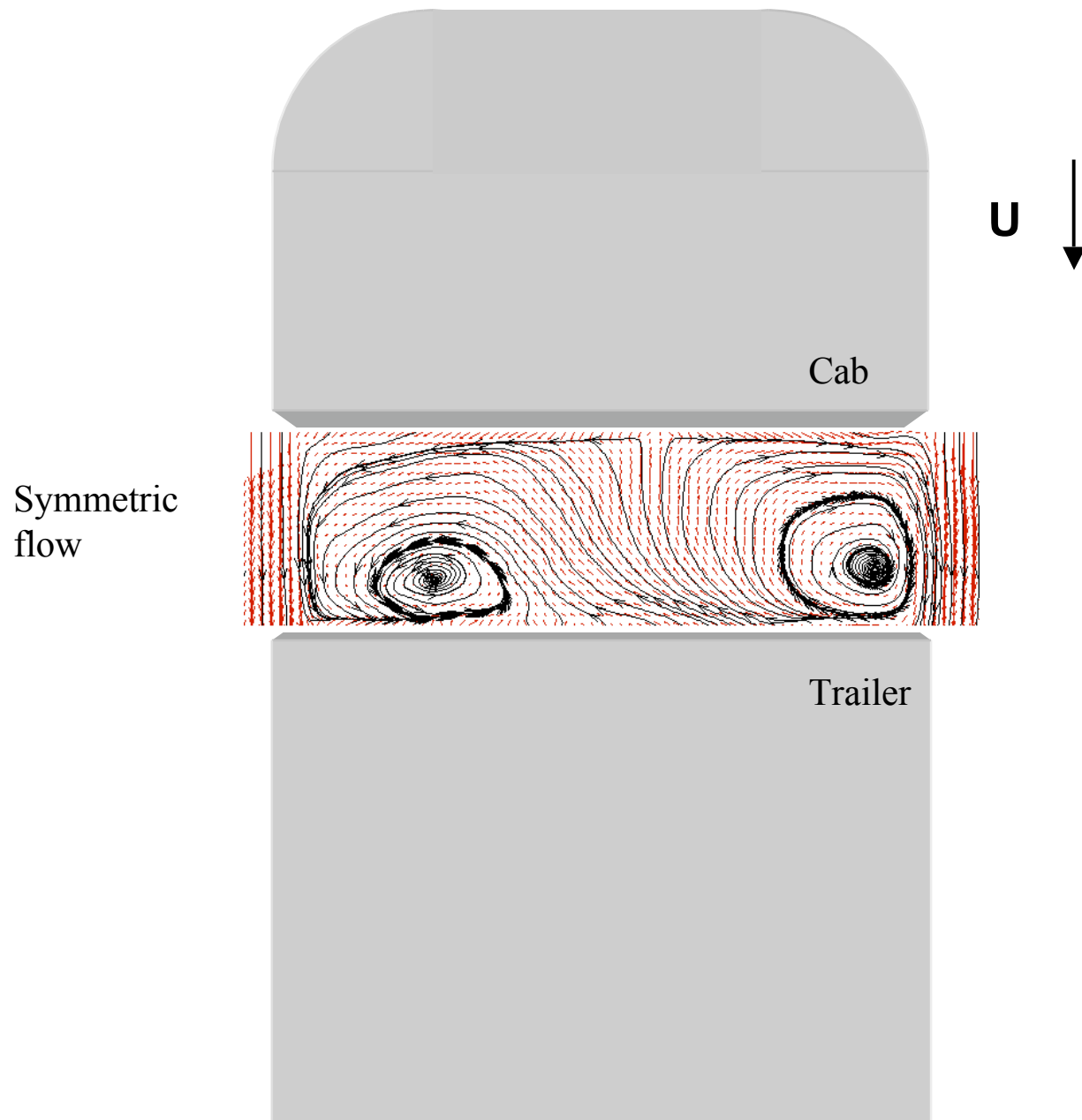


**$G/L = 100\%$**



# Time-averaged streamline patterns

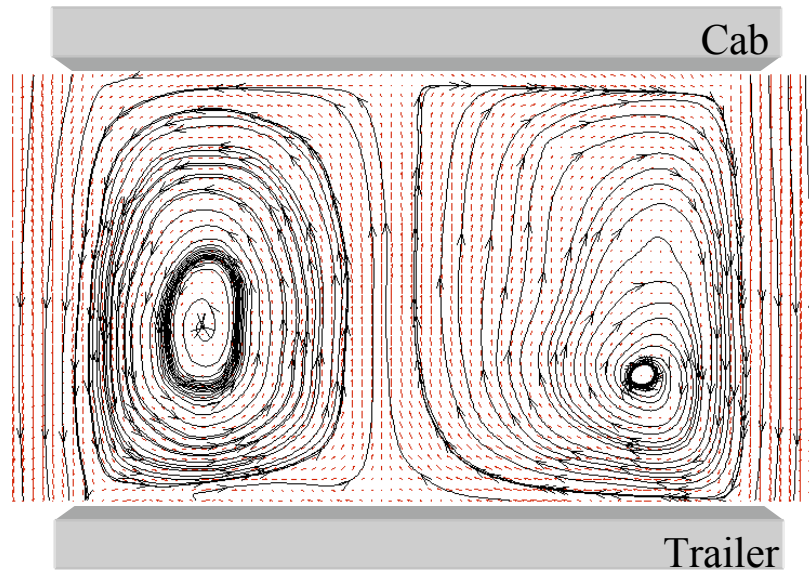
$$G/L = 28\%$$



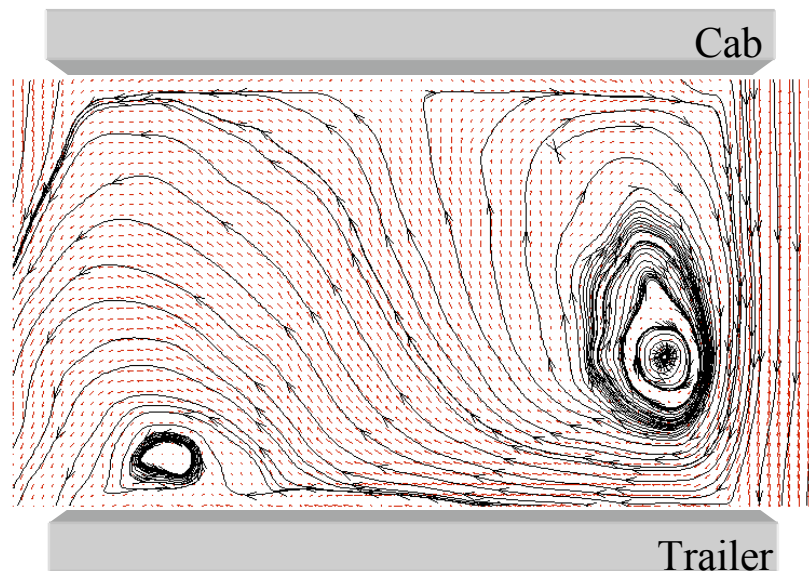
# Time-averaged streamline patterns

$$G/L = 55\%$$

Symmetric  
flow

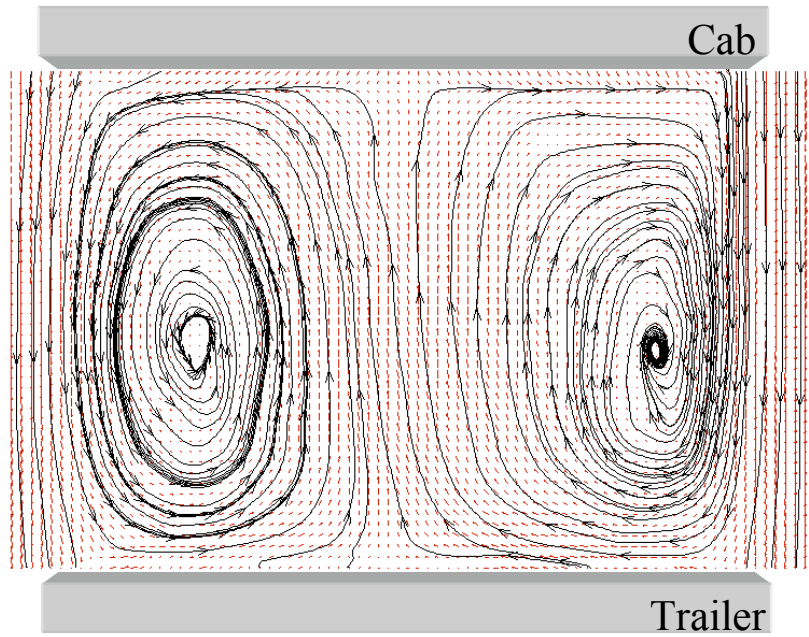


Asymmetric  
flow

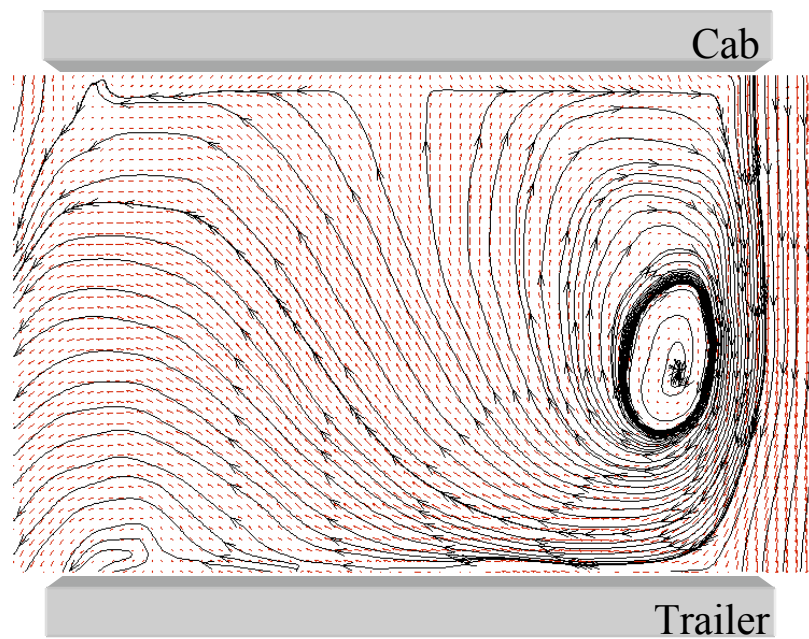


$$G/L = 65\%$$

Symmetric  
flow

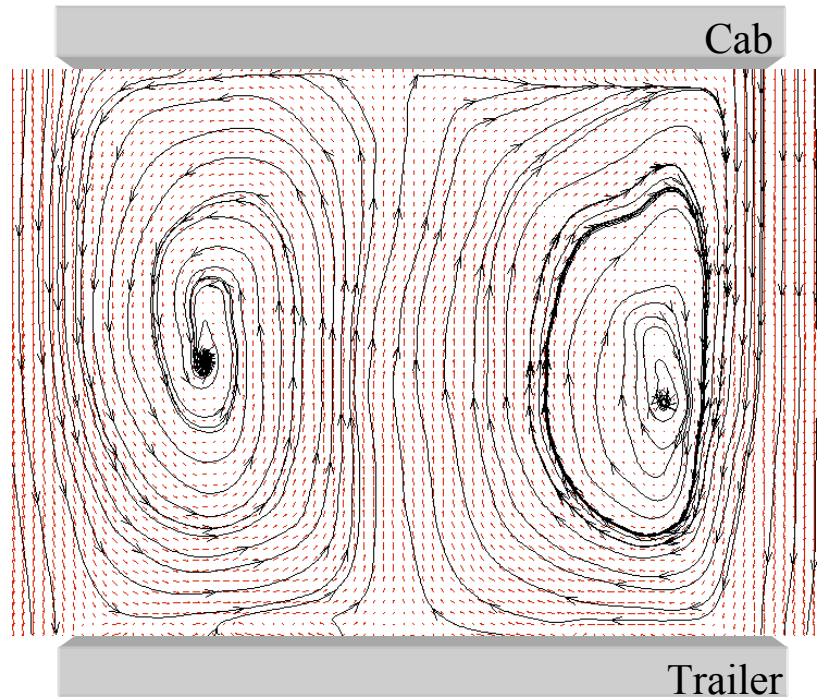


Asymmetric  
flow

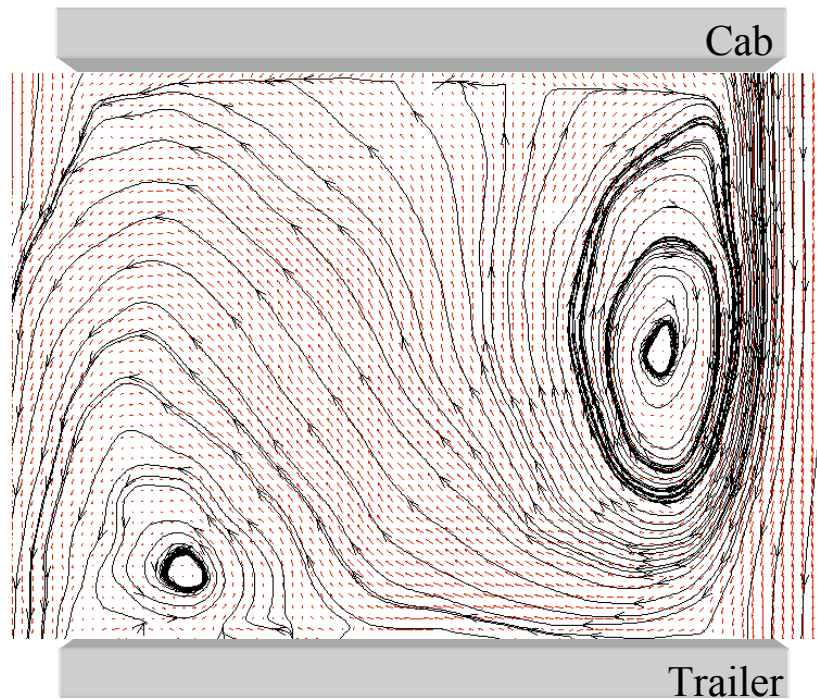


$$G/L = 75\%$$

Symmetric  
flow

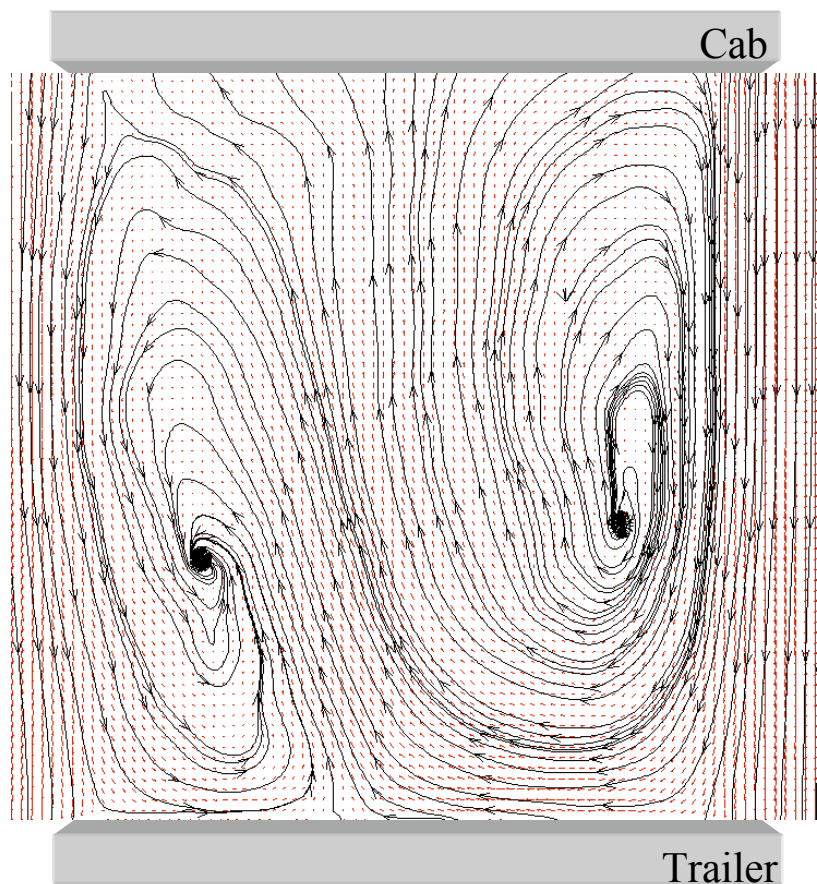


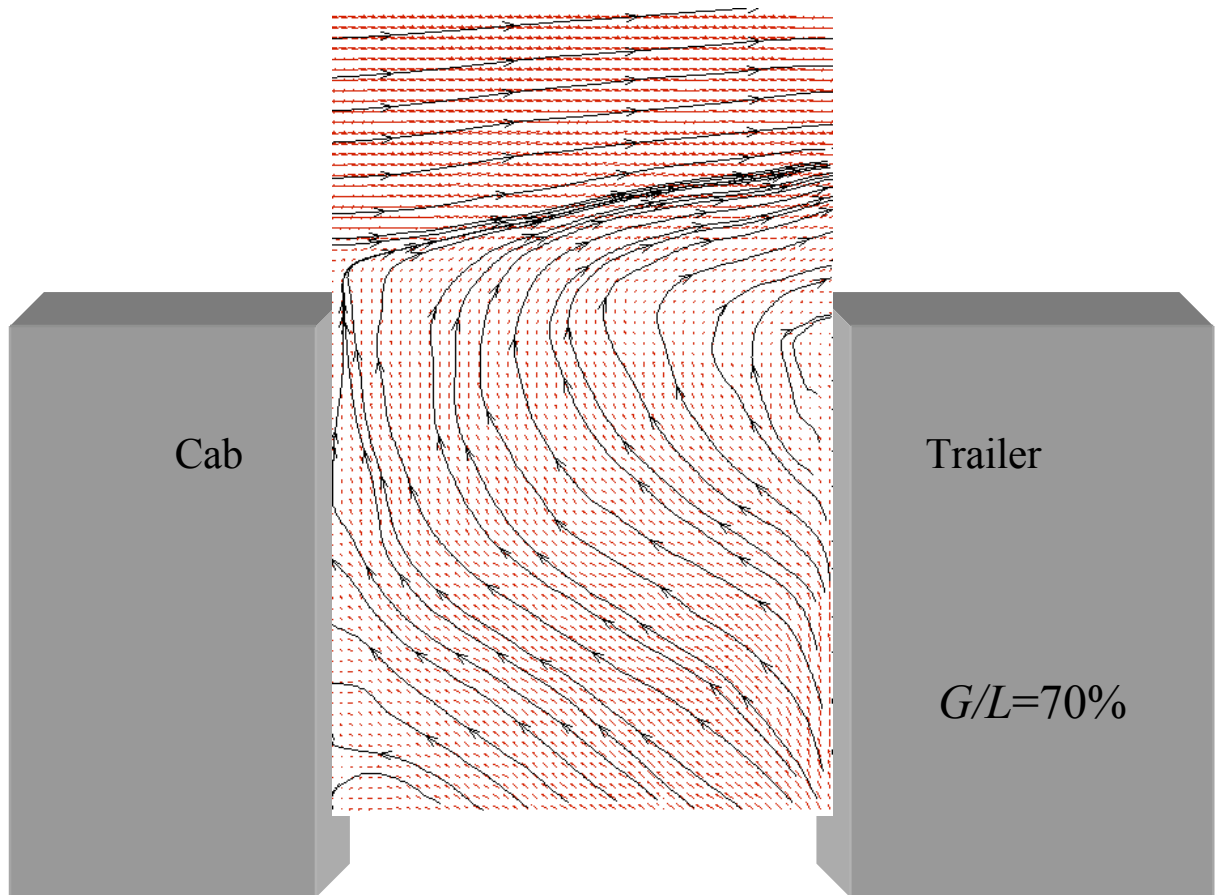
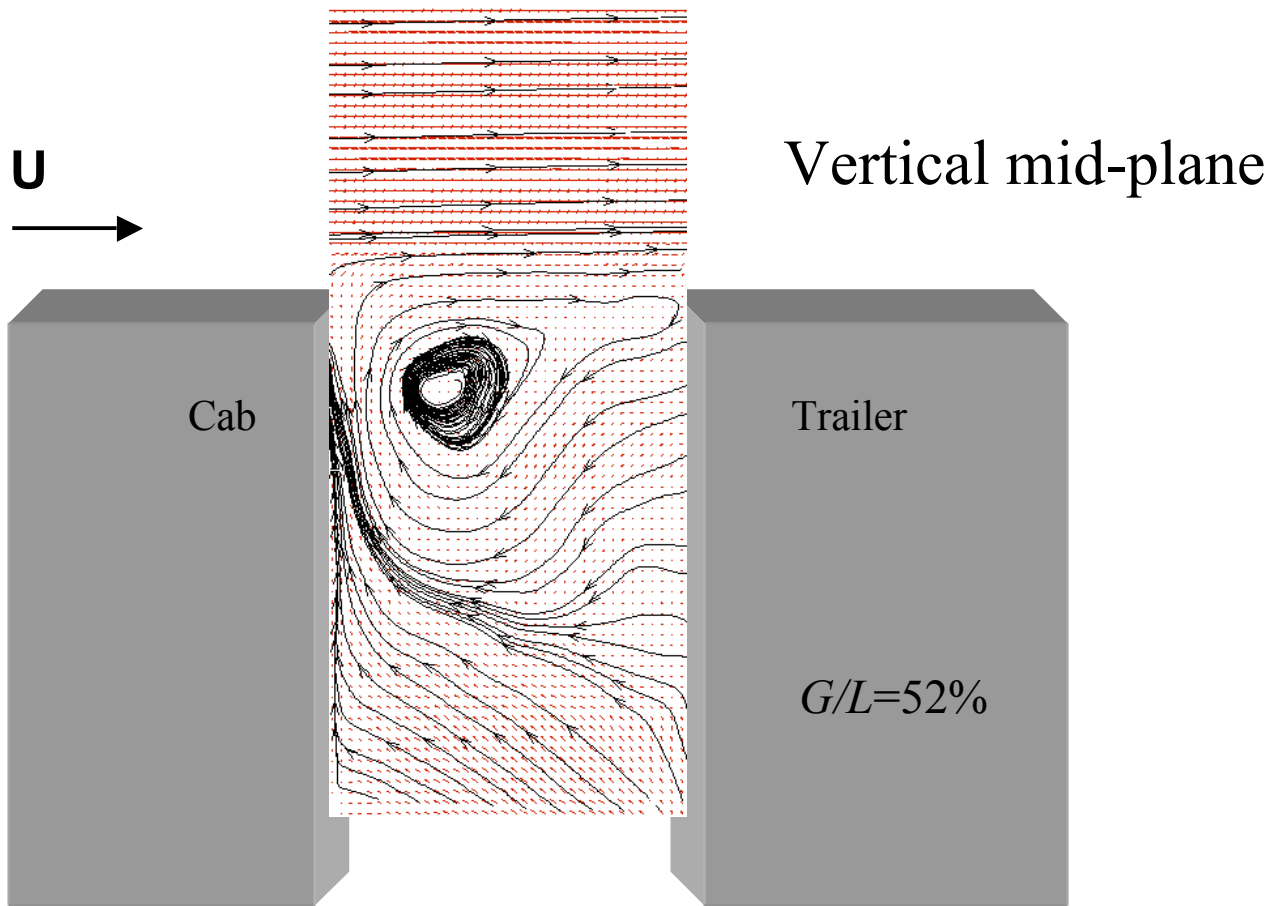
Asymmetric  
flow



$$G/L = 100\%$$

Symmetric  
flow

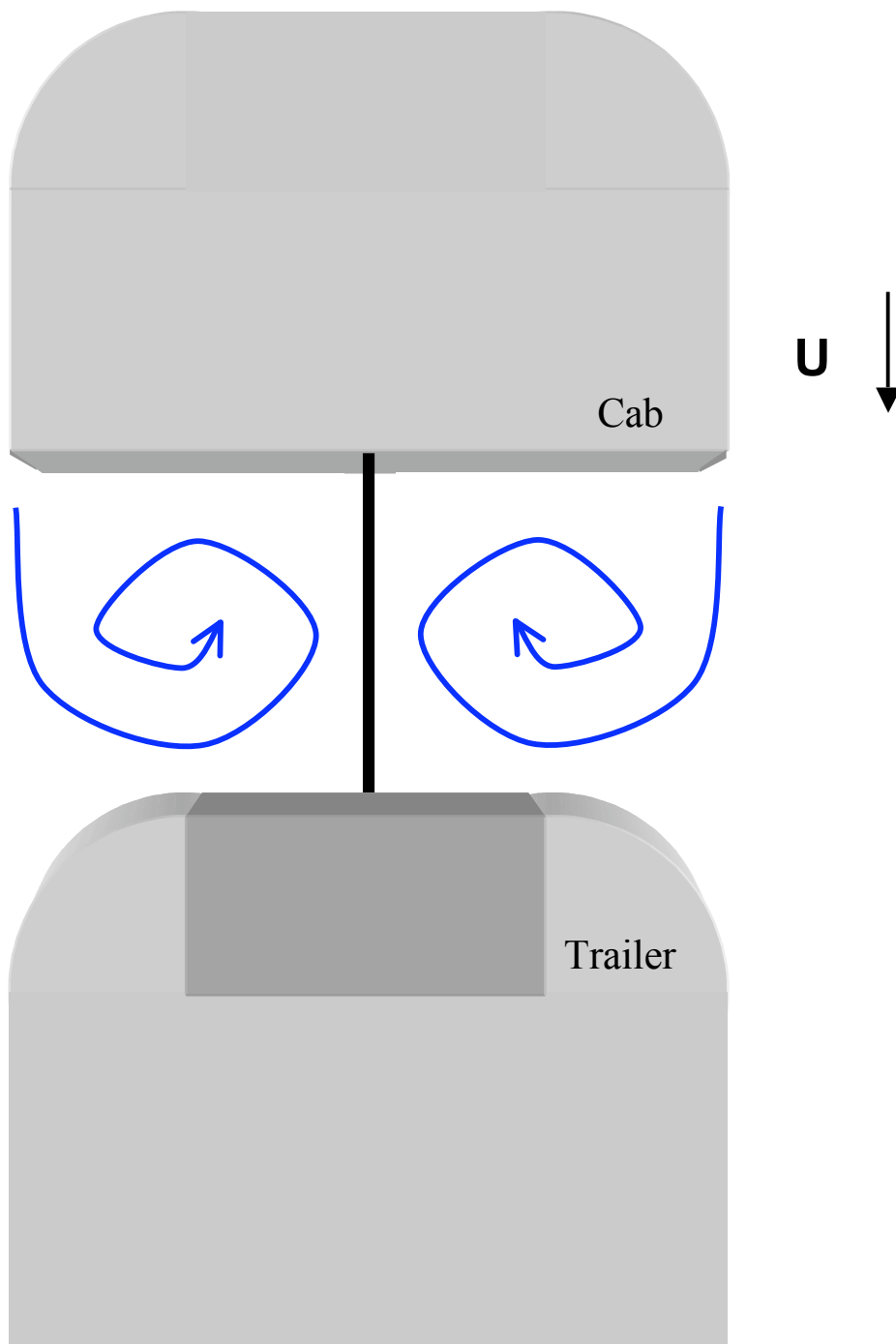




## Conclusions

- A critical gap exists with  $G/L \approx 0.5$
- For  $G/L \approx 0.5$ , the gap flow consists of a relatively stable, symmetric toroidal vortex
- A relatively low drag is obtained
- For  $G/L \geq 0.5$ , the gap cannot support the steady vortex
- The vortex is alternately shed from the gap region, in an unsteady manner
- The relatively smooth flow about the trailer (and tractor) is disrupted, and a large drag results

# Inhibiting flow through the gap



# Future Work

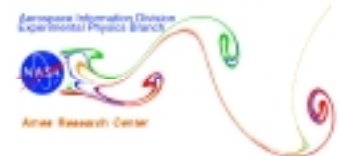
- Include results for various yaw angles
- Include effect of cab extenders and gap divider
- Include trailer with rounded vertical edges
- Refine measurements
  - Collect more samples
  - Utilize additional vertical/horizontal planes
  - Improve velocity estimates near boundaries

# Experimental Measurements of the 1/8th-Scale Ground Transportation System in the NASA Ames 7- by 10-Ft Wind Tunnel

Bruce L. Storms, James T. Heineck,  
Stephen M. Walker, James C. Ross,  
Dave Driver, James Bell

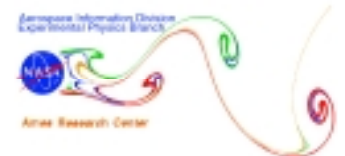
Experimental Physics Branch  
NASA Ames Research Center

1999 DOE Third Workshop on Heavy Vehicle Aerodynamics  
November 14, 1999  
Detroit, MI



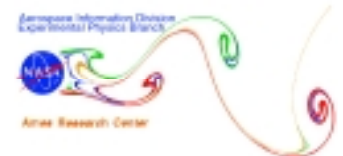
# Outline

- Objectives
- Model Details
- Test Matrix
- Measurements
- Results
- Summary



# Objectives

- Provide experimental data for CFD validation.
  - Both on-body and off-body measurements
  - Time-averaged and limited dynamic data
- Demonstrate a simple drag reduction technique that is easily modeled in computations.

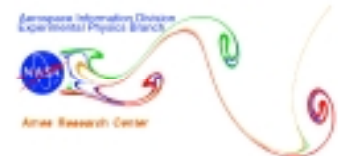


## Ground Transportation System (GTS) Model

- Simplified Geometry
  - Cab over design
  - No gap
  - No wheels
- 1/8th Scale
  - Length: 97.5 in.
  - Height: 17.75 in.
  - Width: 12.75 in.

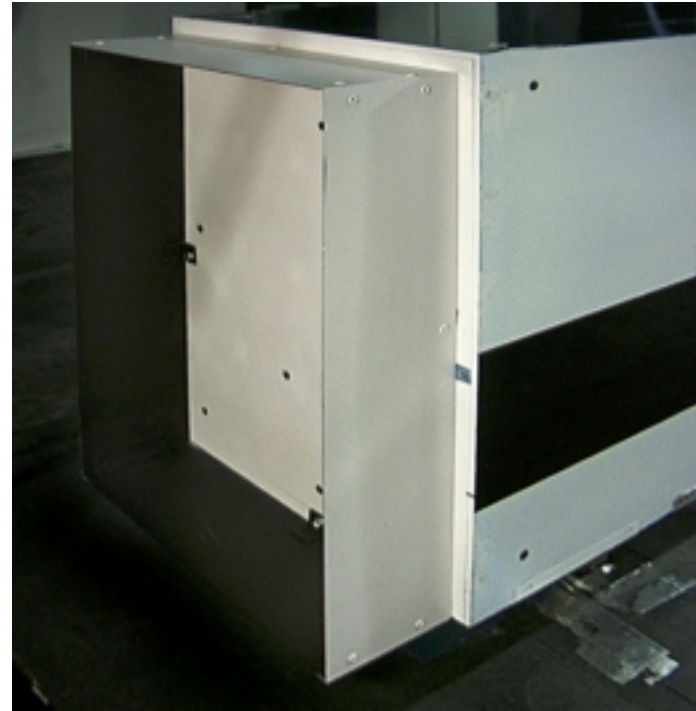


Installation of GTS model in NASA Ames 7x10 wind tunnel

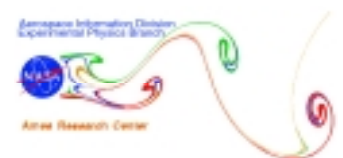


## Drag Reducing Boattail Plates

- Developed by Continuum Dynamics, Inc.
- Dimensions:
  - Length: 3.75 in.
  - Height: 17.125 in.
  - Width: 11.25 in.
- Full-Scale Length = 2.5 ft

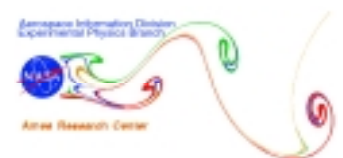


Boattail plates installed on back of truck



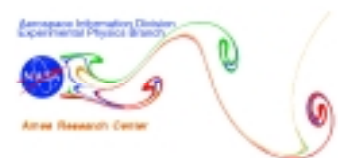
## Test Matrix

- Model configuration: w & w/o boattail plates
- Yaw angle:  $\pm 14$  deg
- Tunnel Conditions:
  - Mach = 0.27 and 0.10
  - Reynolds number = 2 million and 740,000
    - Full-Scale Re = 5 - 6 million
  - Re variation from 300,000 to 2 million (zero yaw)

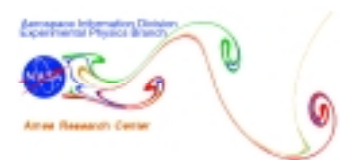
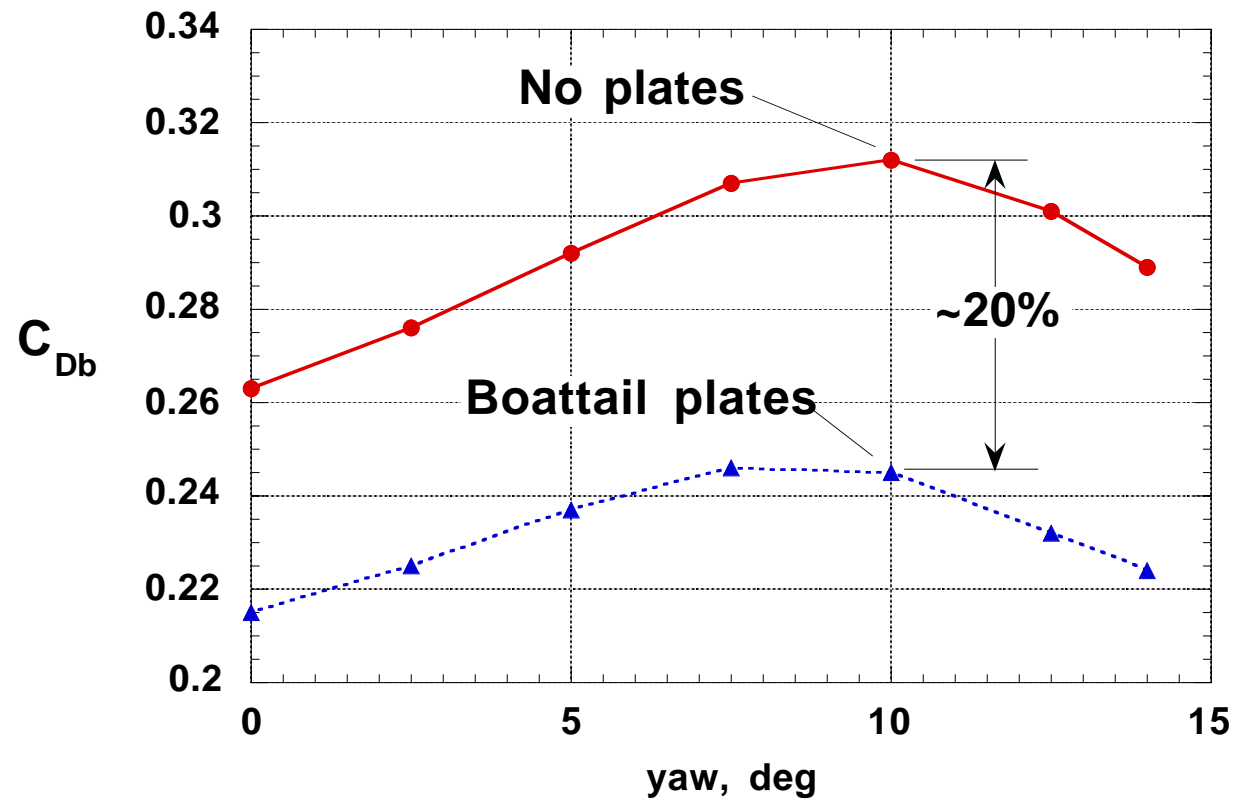


## Measurements

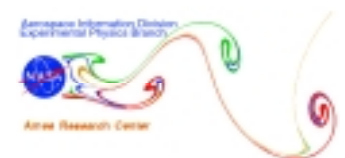
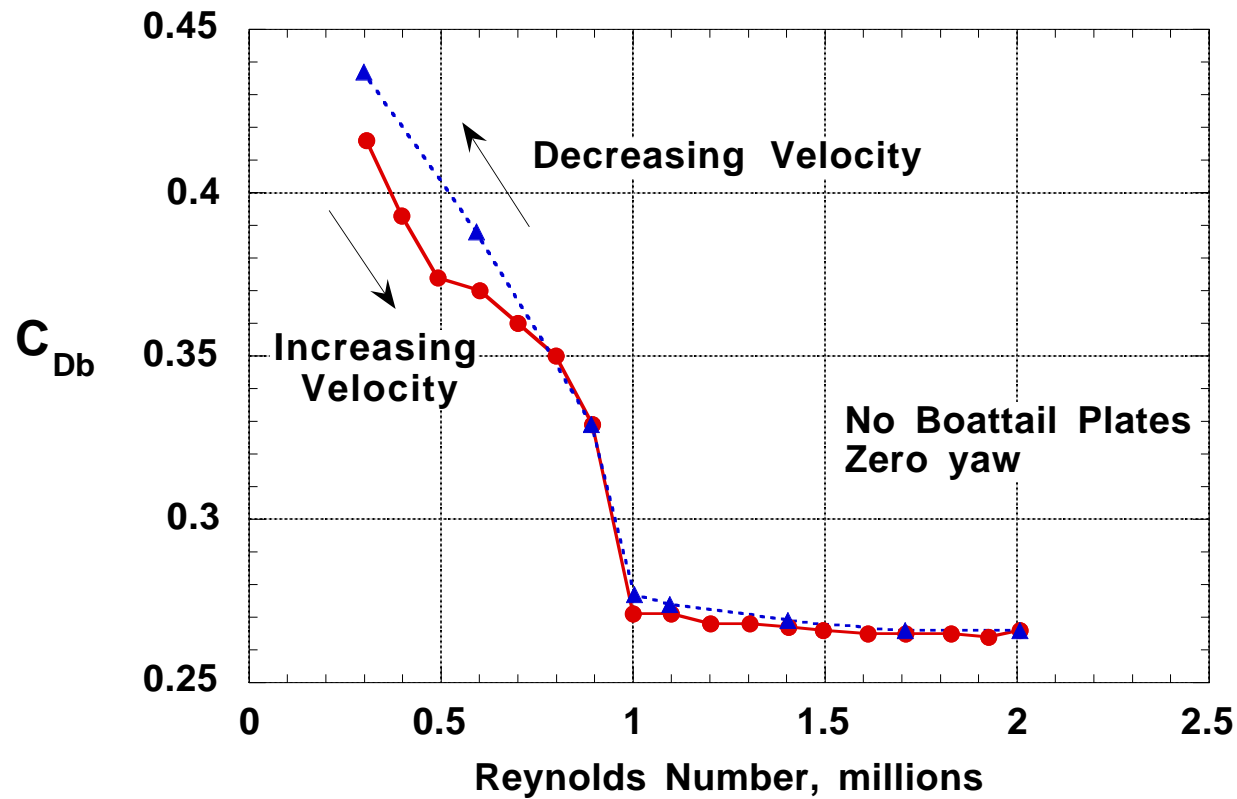
- Forces and moments
- Surface pressures
  - Static pressure taps
  - Pressure-Sensitive Paint
  - Unsteady pressure
- Skin friction from Oil-Film Interferometry
- Separation/Transition detection
- 3D Particle Image Velocimetry



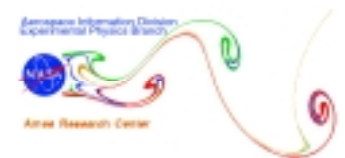
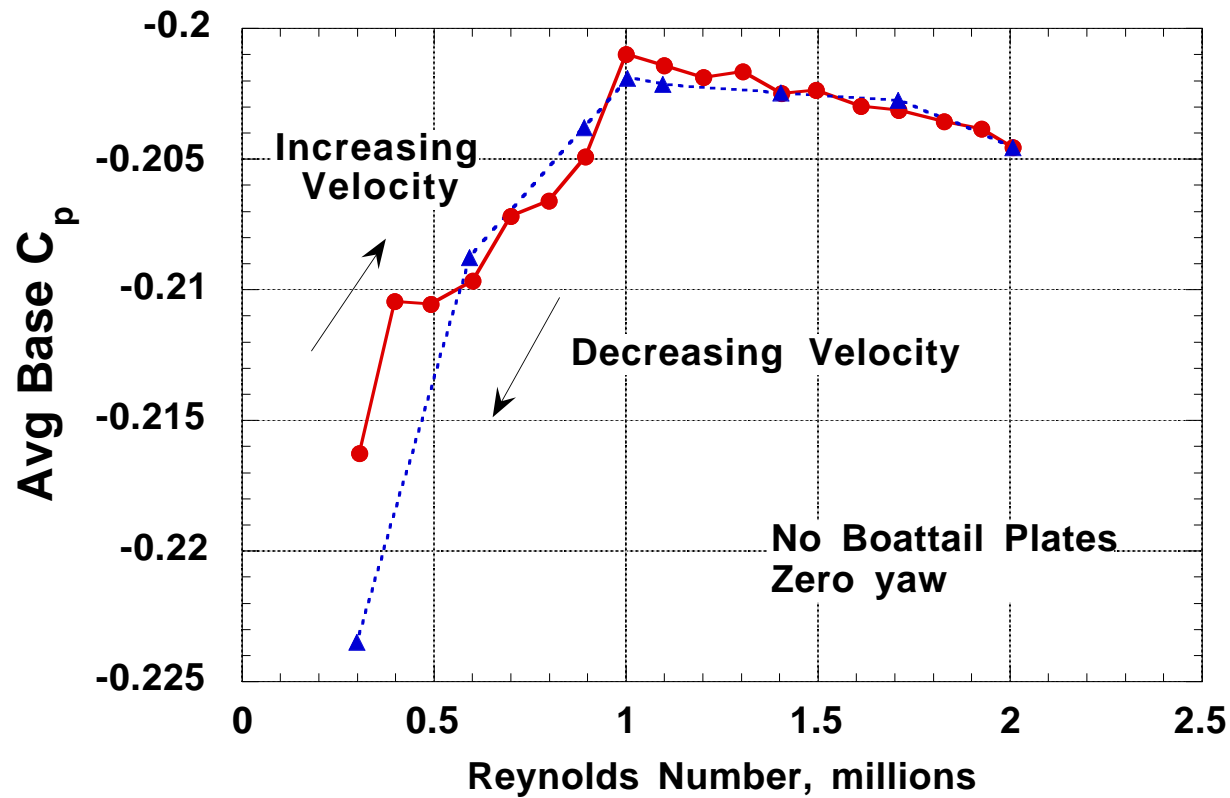
# Effect of Boattail Plates on Drag



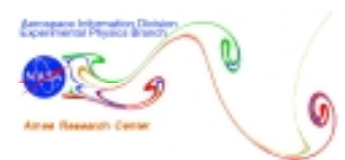
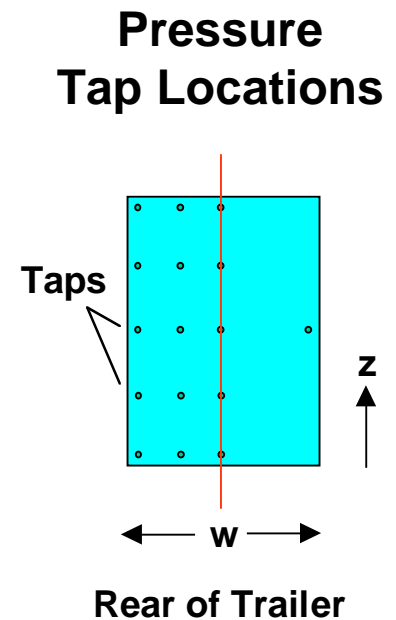
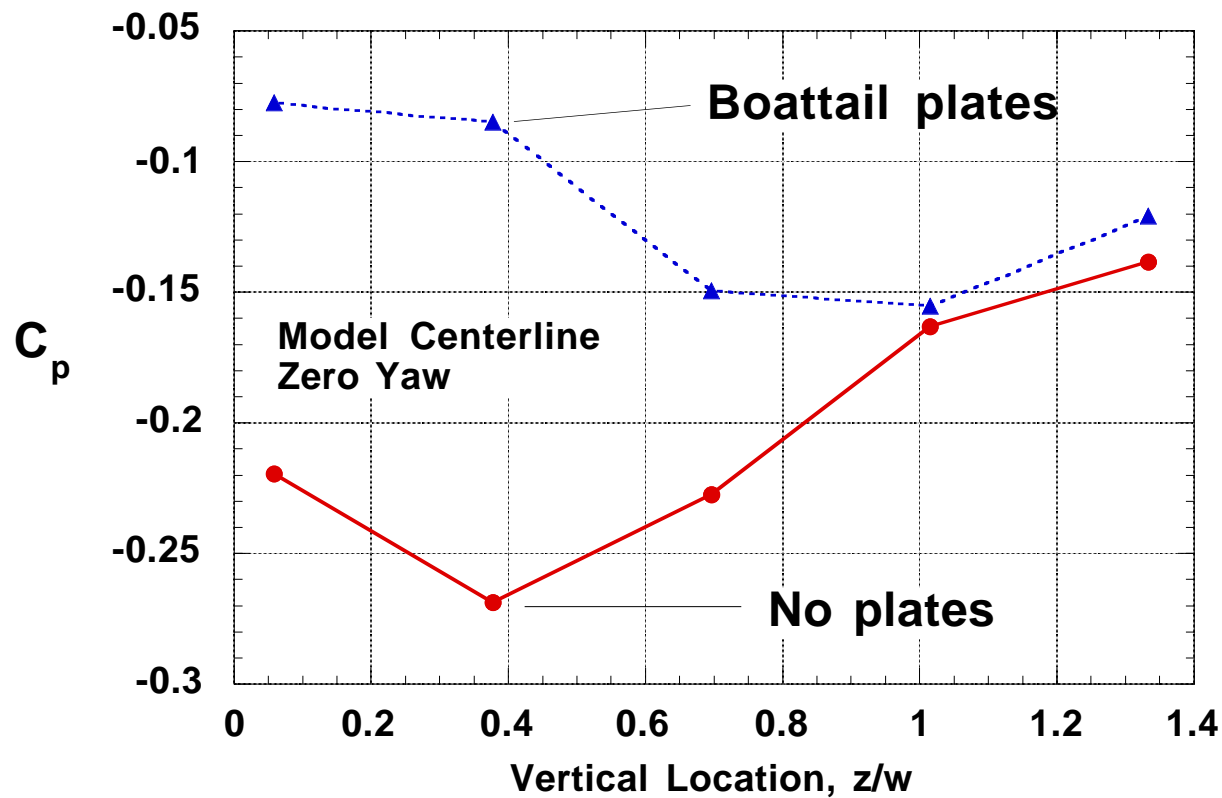
# Effect of Reynolds Number on Drag



# Effect of Reynolds Number on Base Pressure

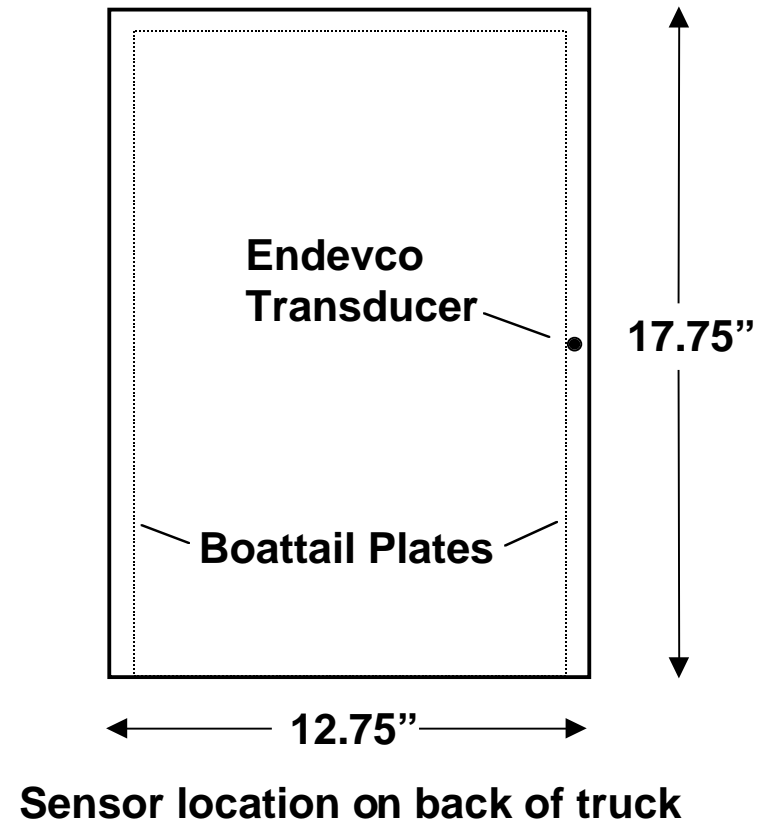


# Effect of Boattail Plates on Base Pressure



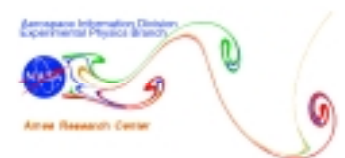
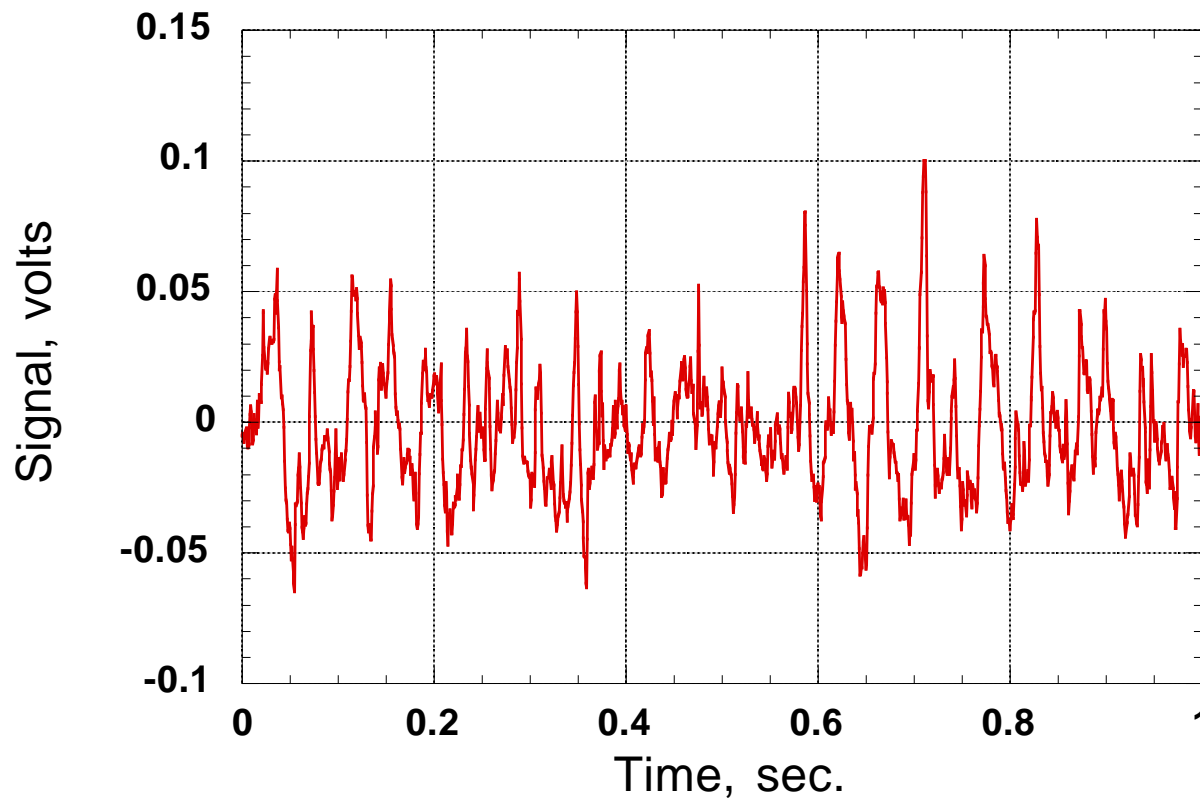
## Unsteady Pressure Measurement

- 15 psia transducer, AC-coupled
- Mid-height on right side of rear door
- Center of transducer is 0.25 inch from side edge
- Measurements made w/ and w/out boattail plates



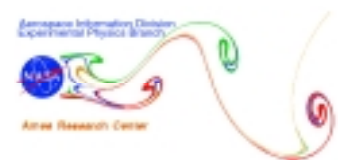
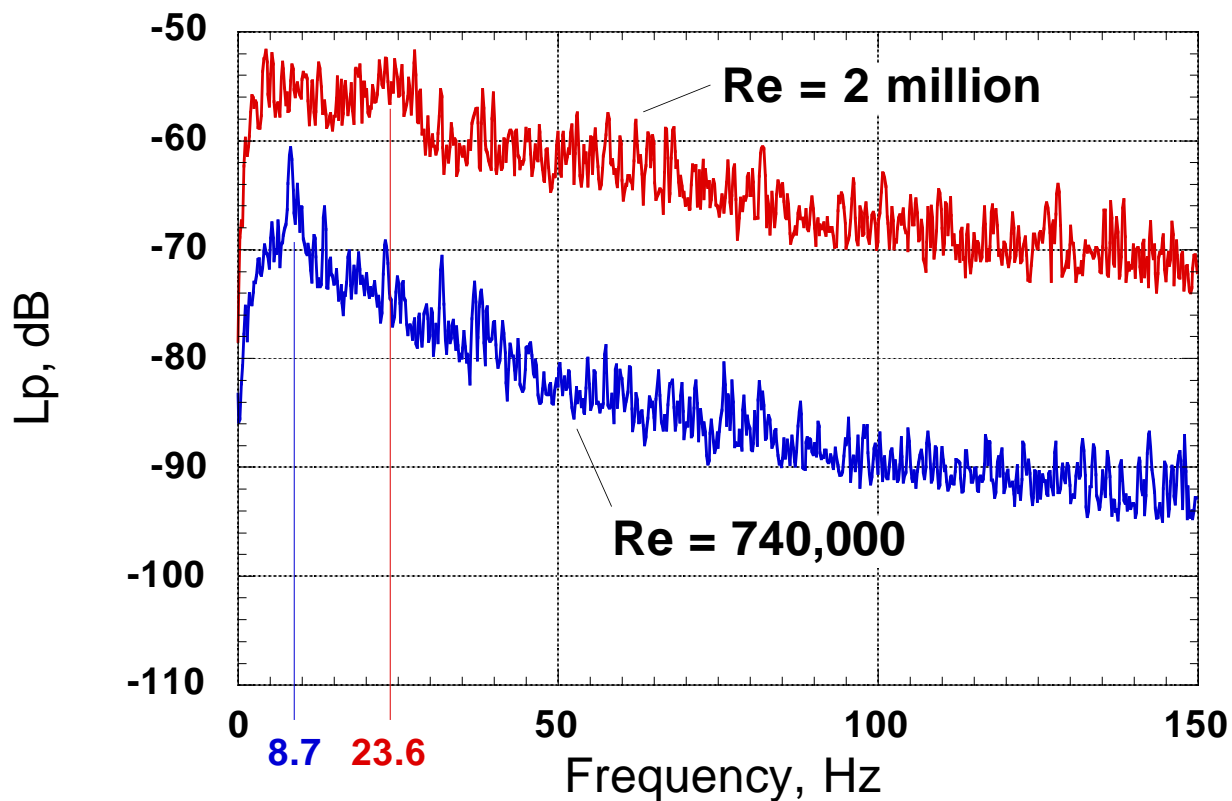
# Unsteady Pressure Signal

No Boattail plates, Yaw = 0 deg, Re = 2 million



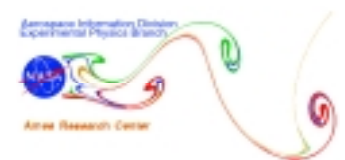
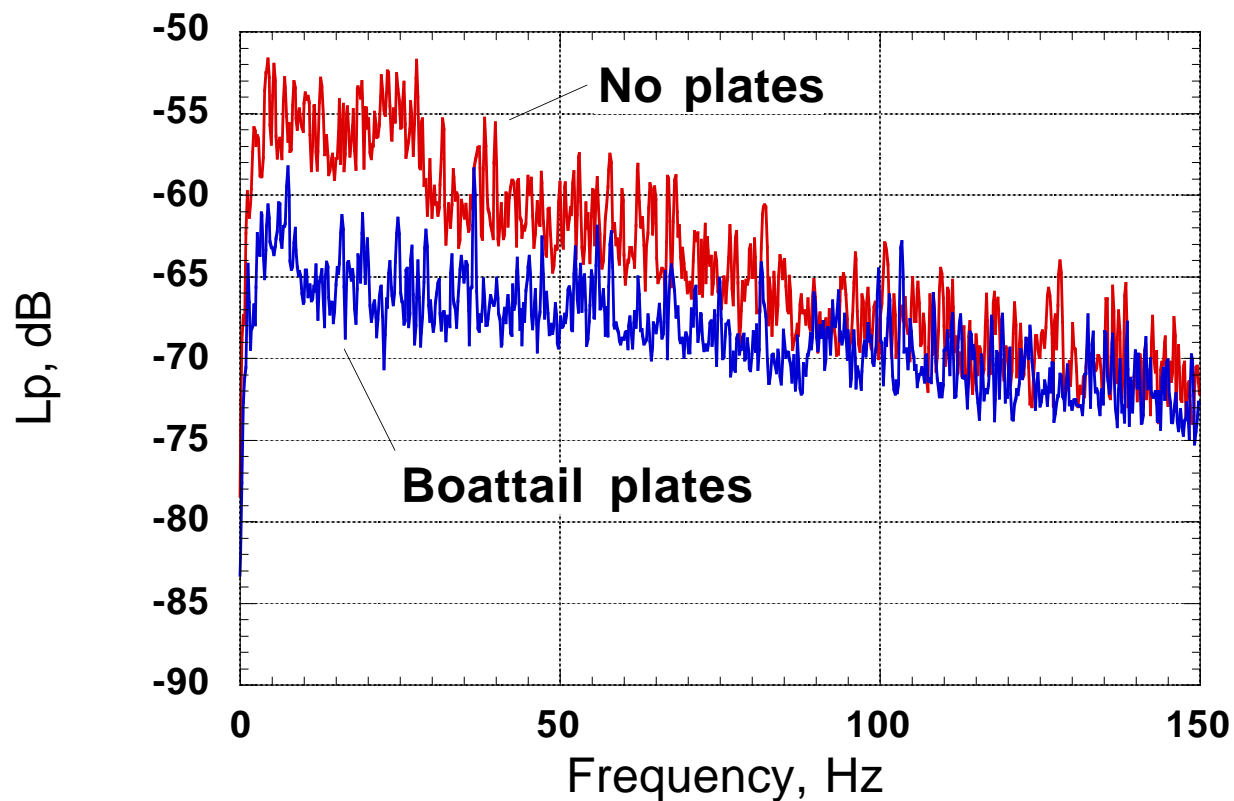
# Effect of Reynolds Number on Unsteady Pressure Spectra

No Boattail plates, Yaw = 0 deg

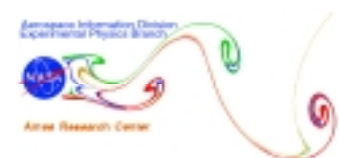
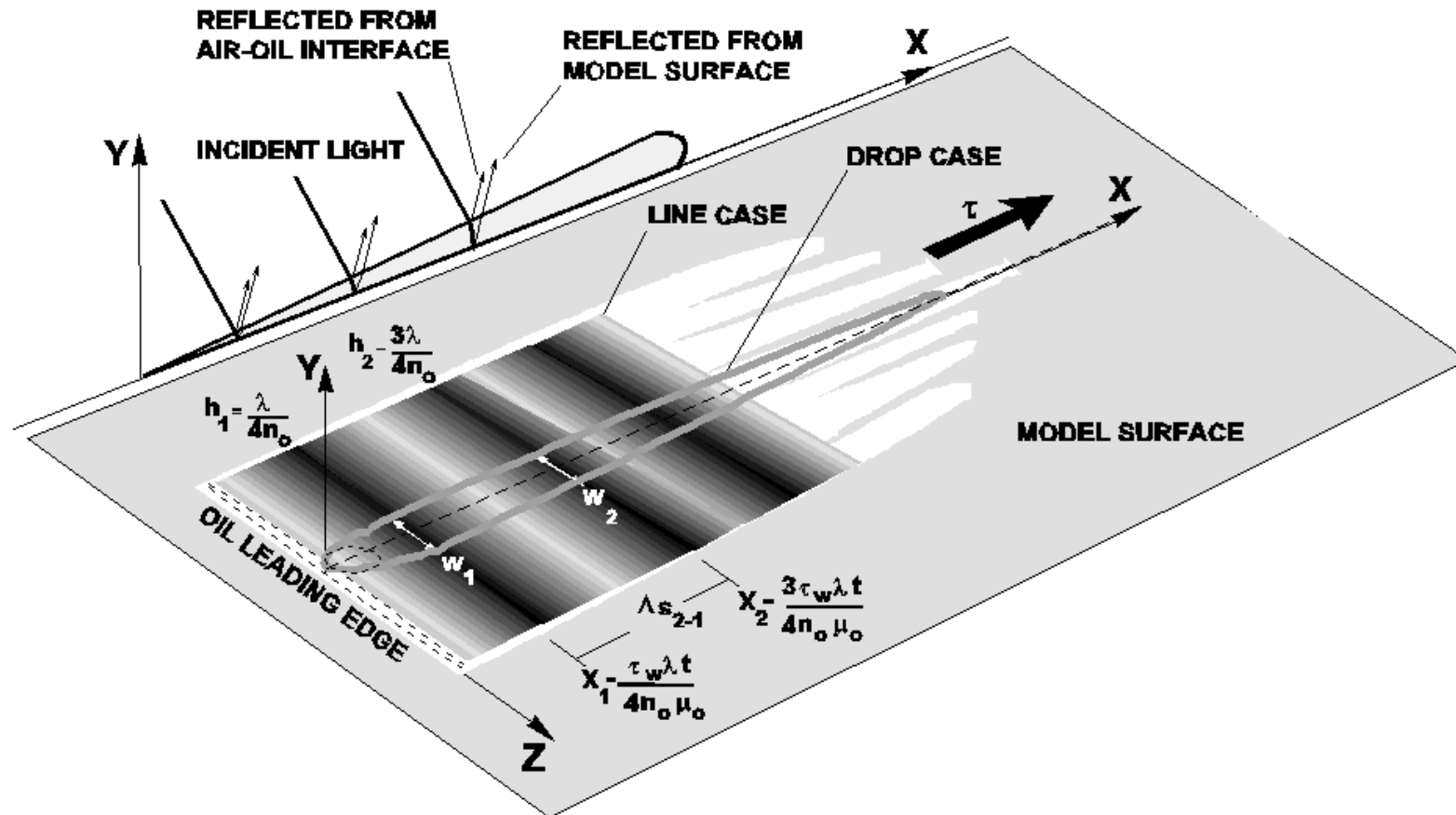


# Effect of Boattail Plates on Unsteady Pressure Spectra

Yaw = 0 deg, Re = 2 million



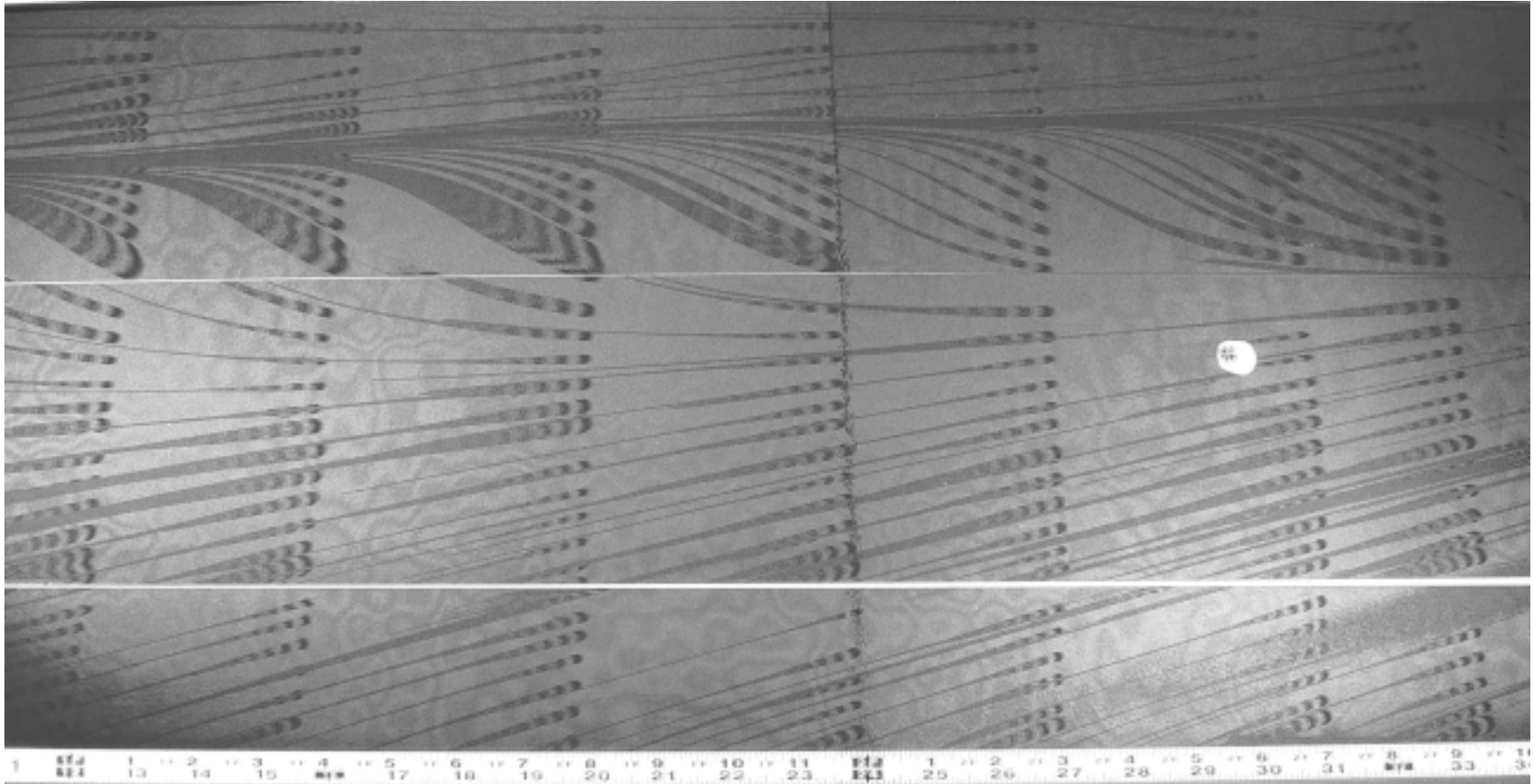
# Oil-Film Interferometry



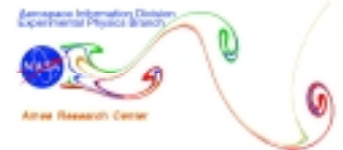
# Oil-Film Interferometry



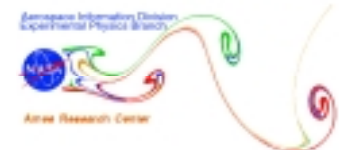
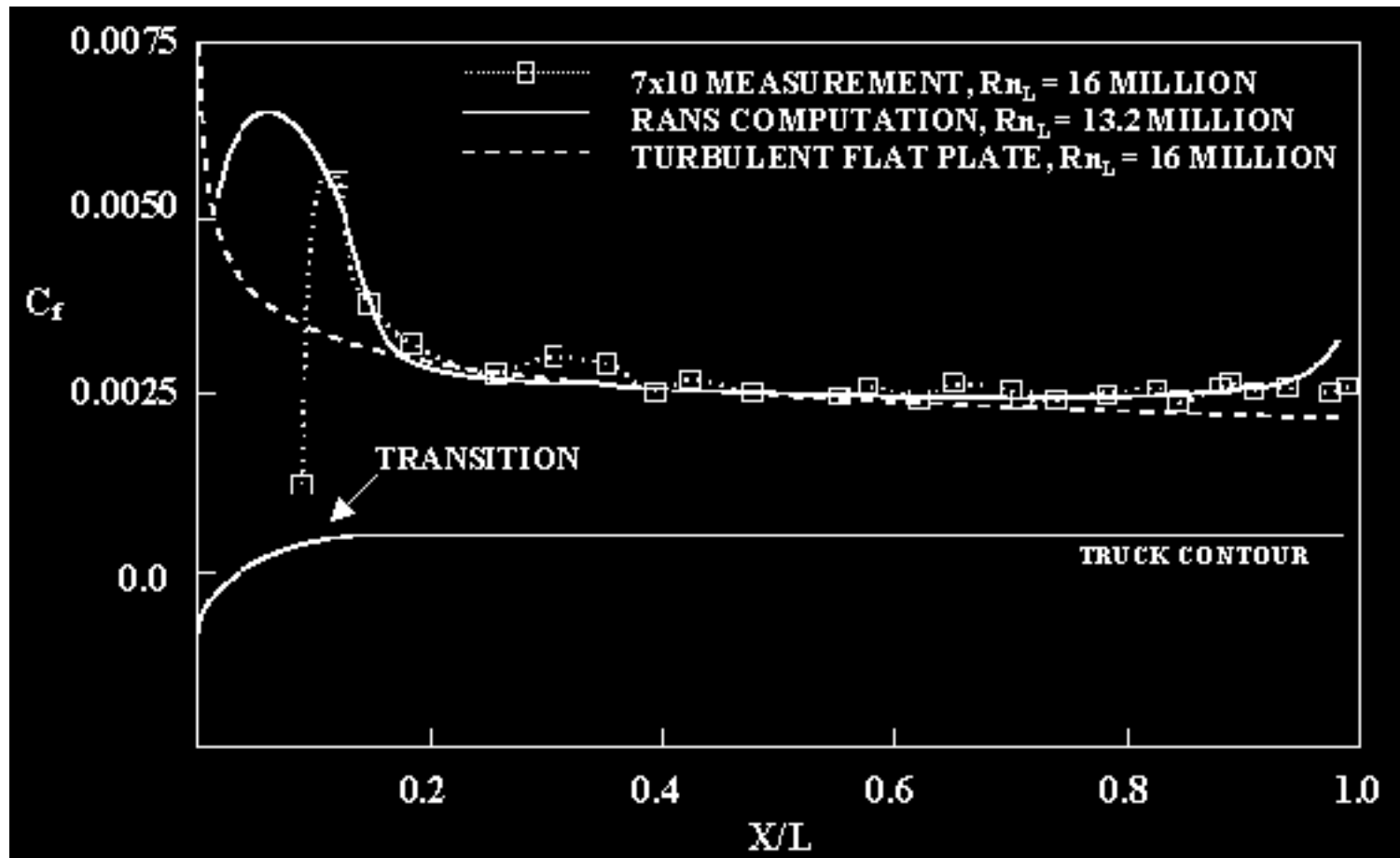
Top View of Trailer at 10-deg Yaw, No Boattail plates



Skin friction proportional to fringe spacing



# Oil-Film Interferometry

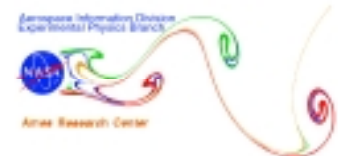


## Transition/Separation Detection with Hot Film

- Conducted by Tao Systems under SBIR
- 64 sensors on right side; 4 configurations
- RMS and intermittency factor reveal transition
- Phase correlations determine separation and reattachment

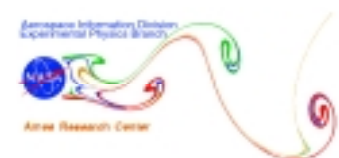
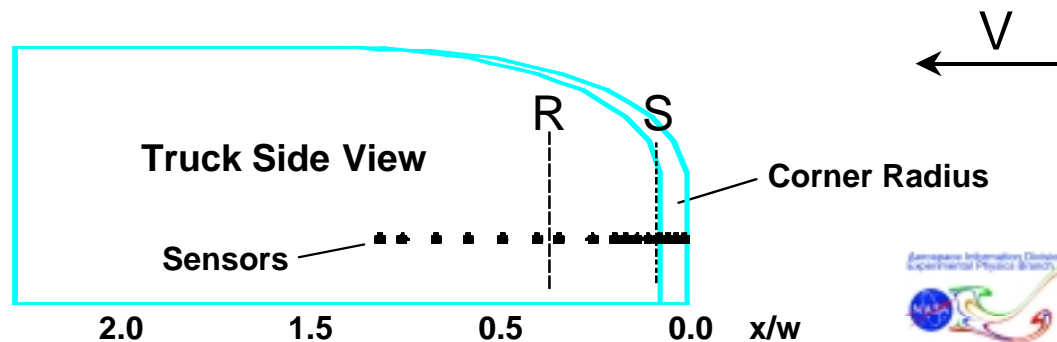
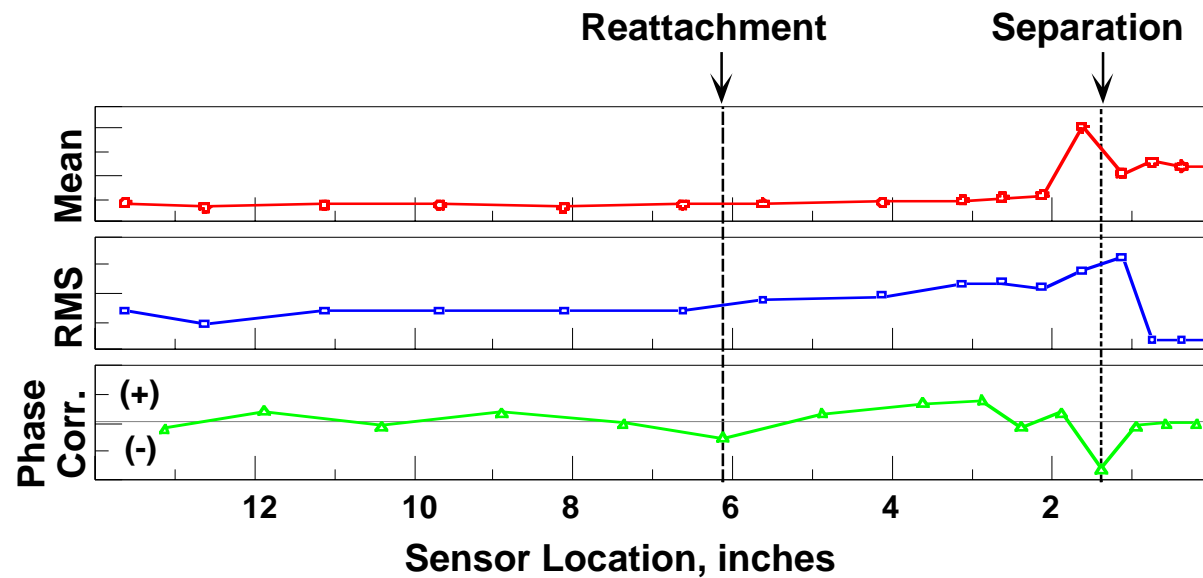


Hot-film sensors installed on GTS model



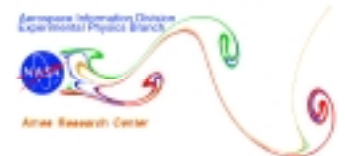
# Hot Film Results

No Boattail plates, Yaw = 10 deg,  $Re = 2$  million



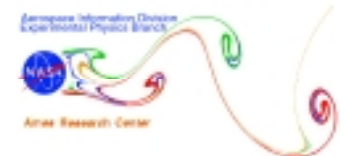
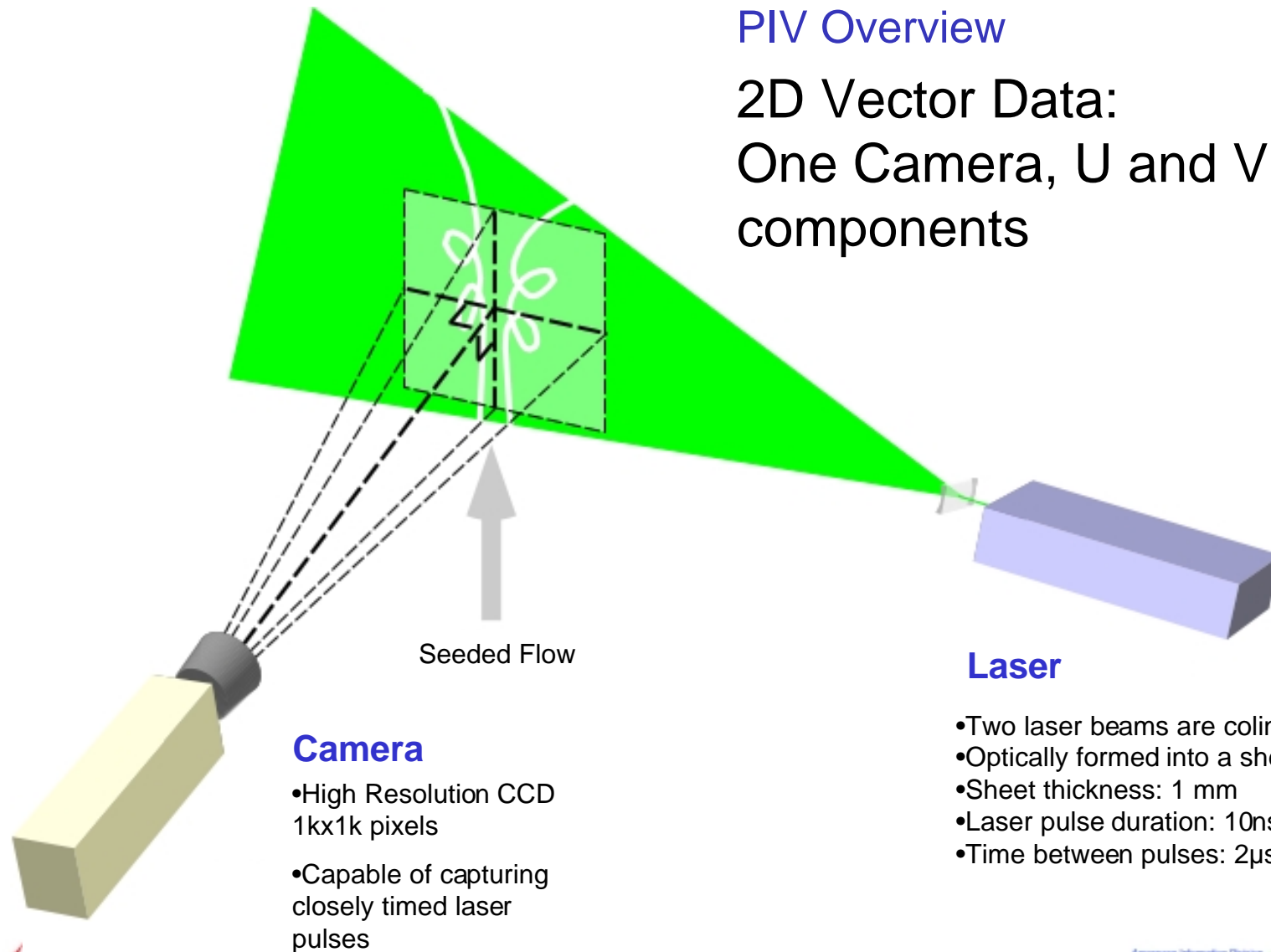
# Particle Image Velocimetry: An Overview

- Produces vector data for a plane in a flow field
- Tracks flow-tracing particles in time using pulsed lasers
- Digital cameras record the particle displacement
- Image processing software calculates the direction and magnitude of displacements

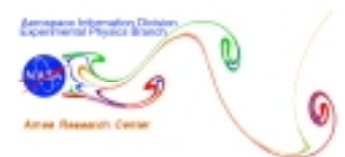
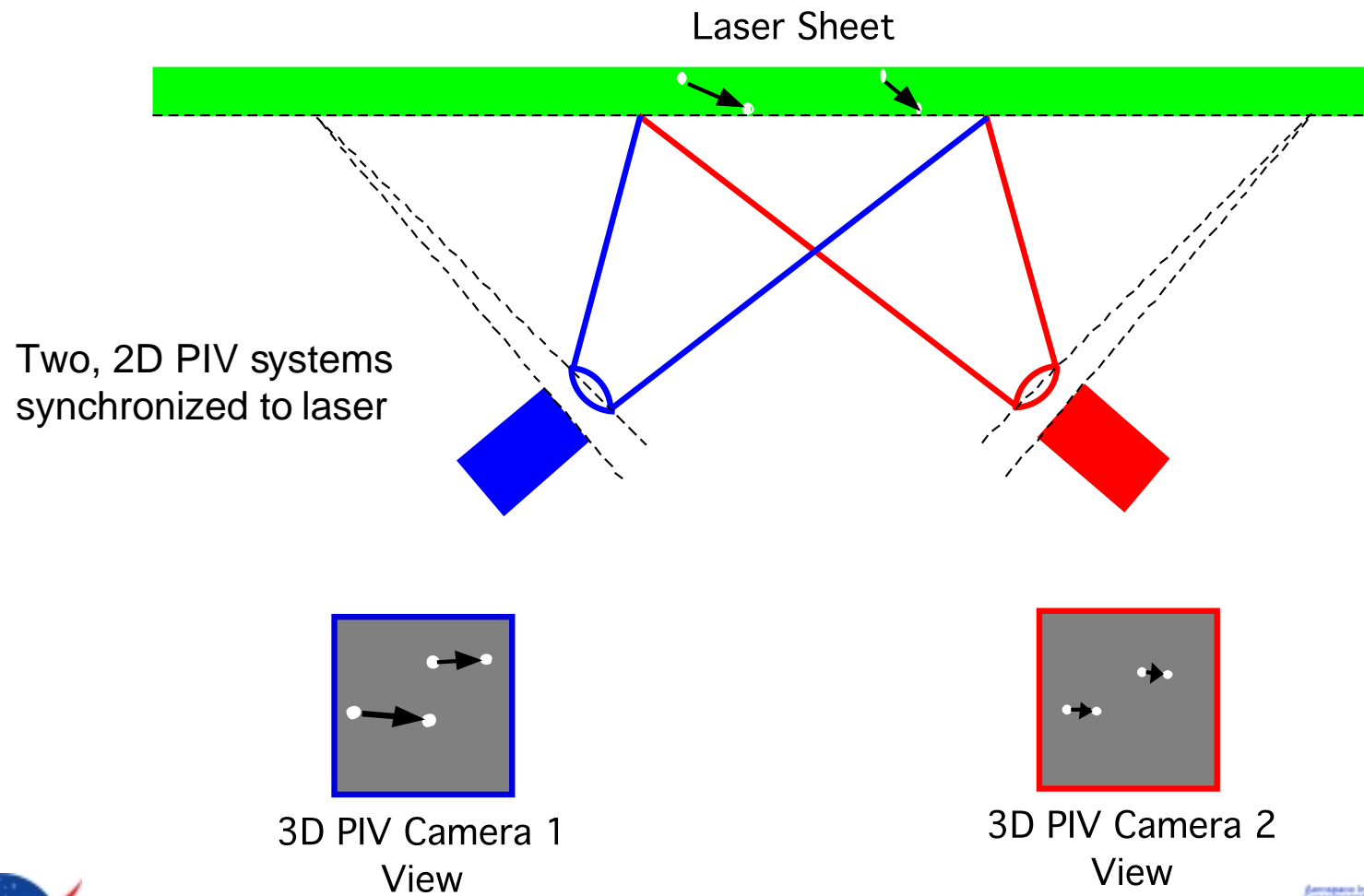


## PIV Overview

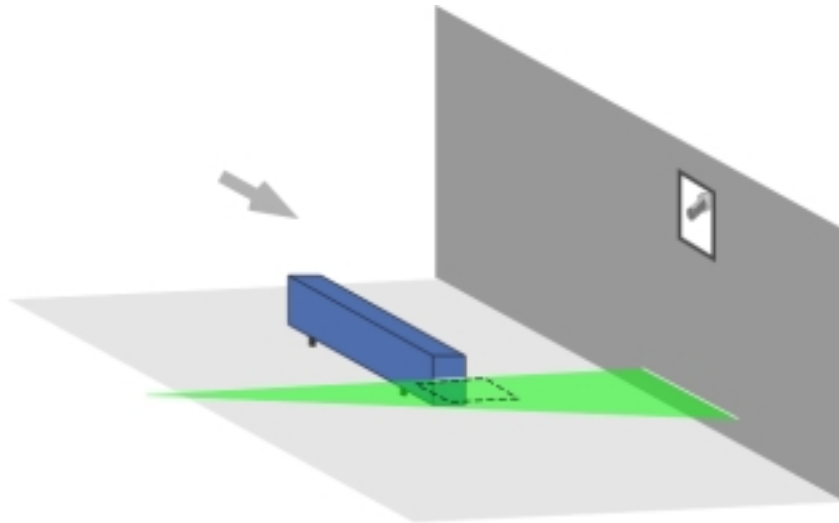
2D Vector Data:  
One Camera, U and V  
components



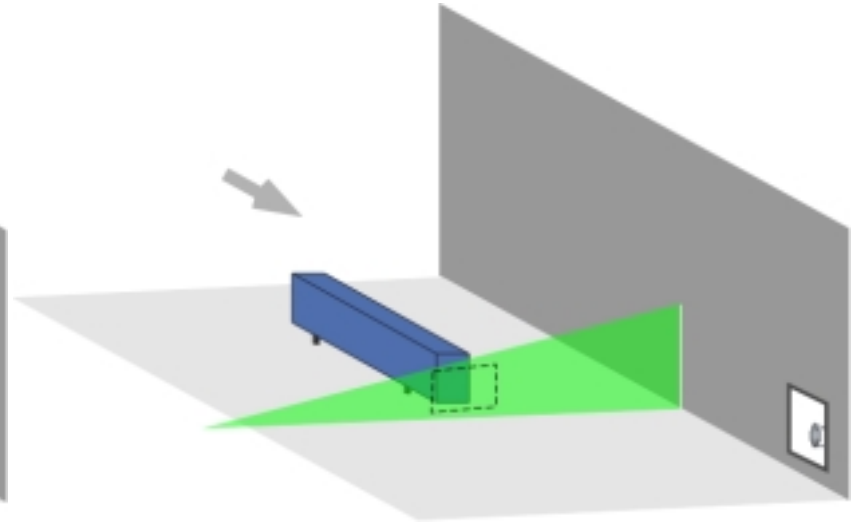
## 3D PIV: Stereoscopic Perspective Difference



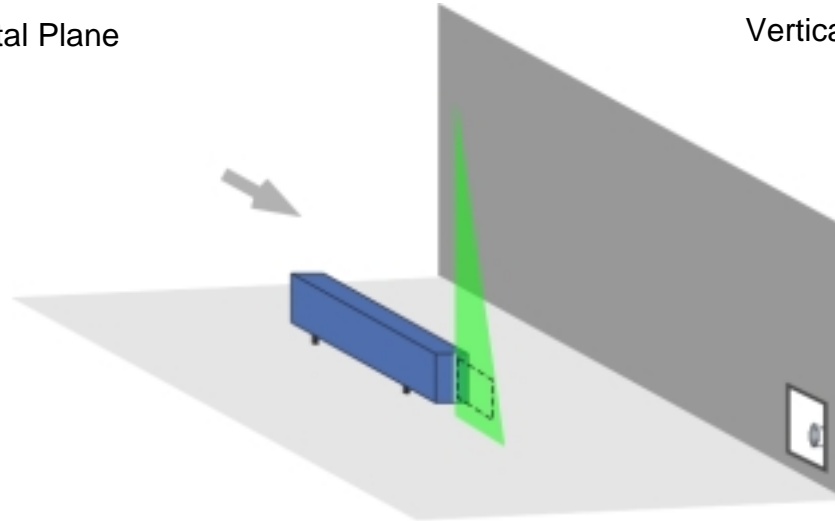
## Laser Sheet and Camera Orientations



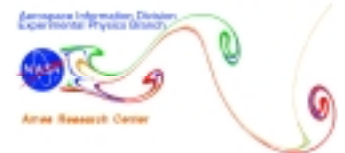
Horizontal Plane



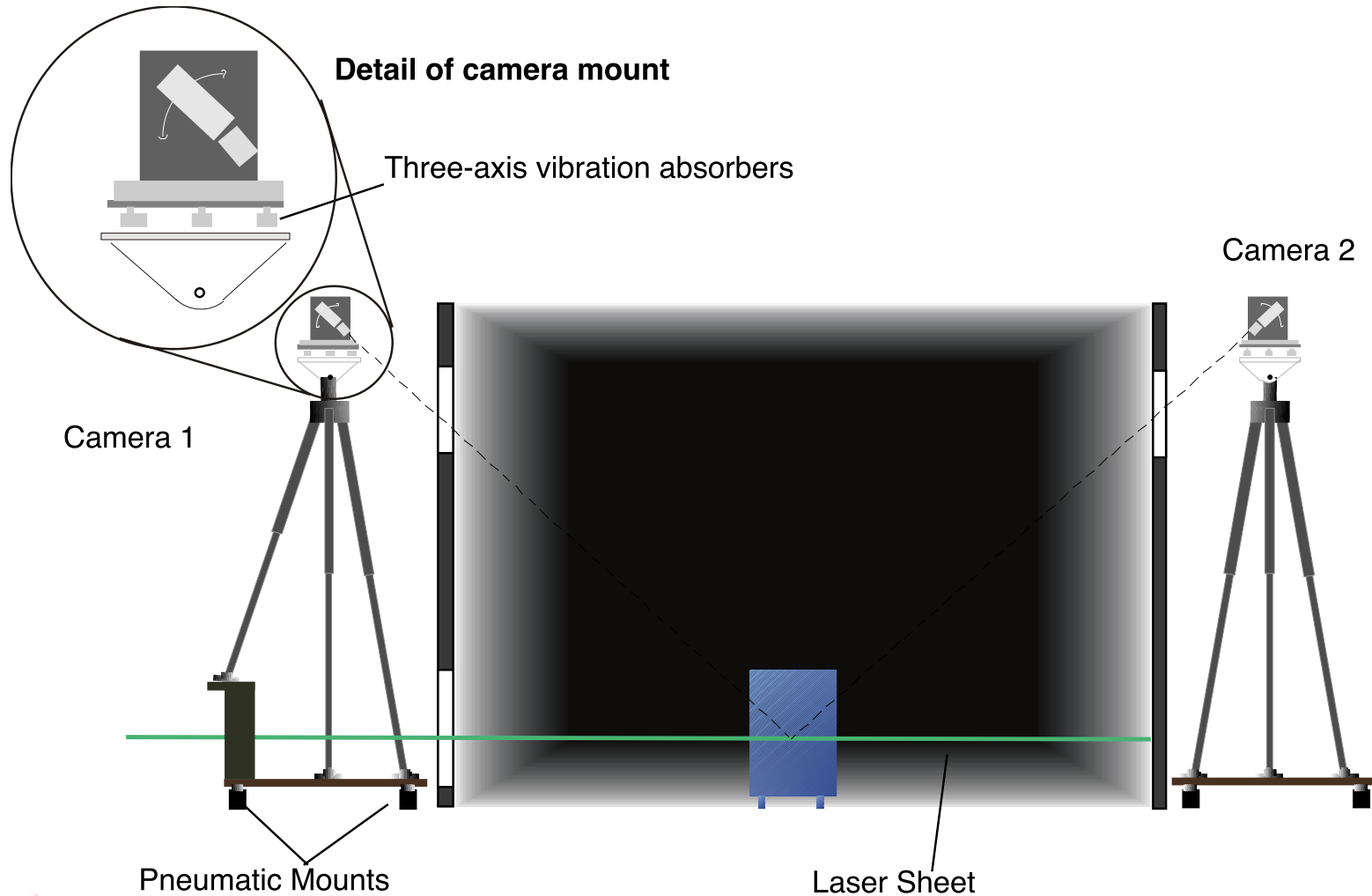
Vertical Cross-stream Plane



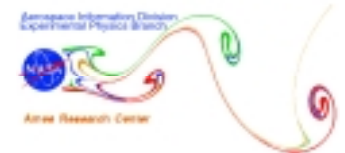
Vertical Streamwise Plane

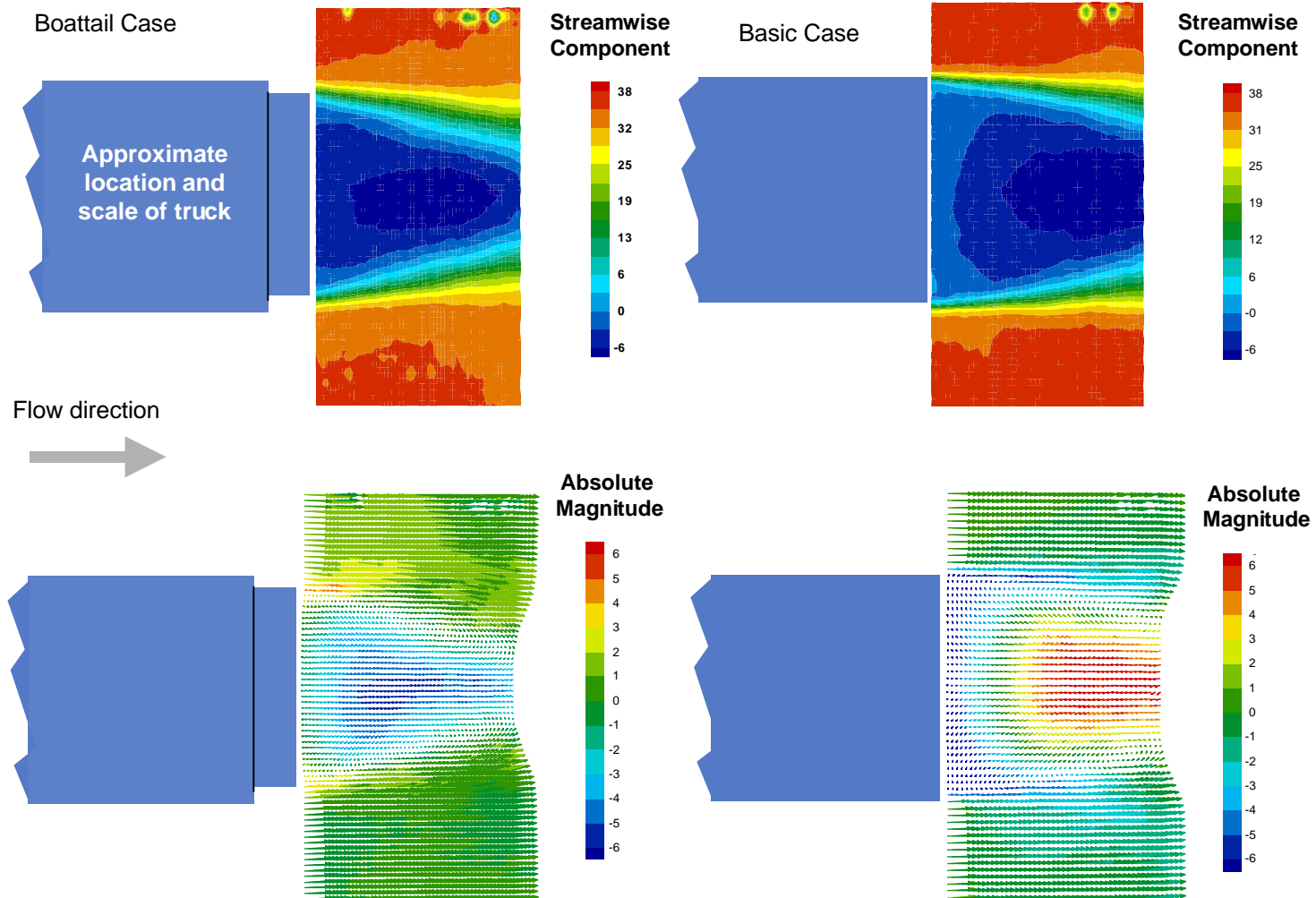


## 3D PIV in the NASA 7x10

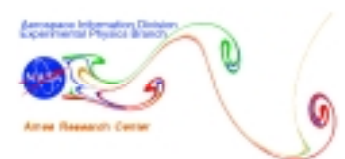


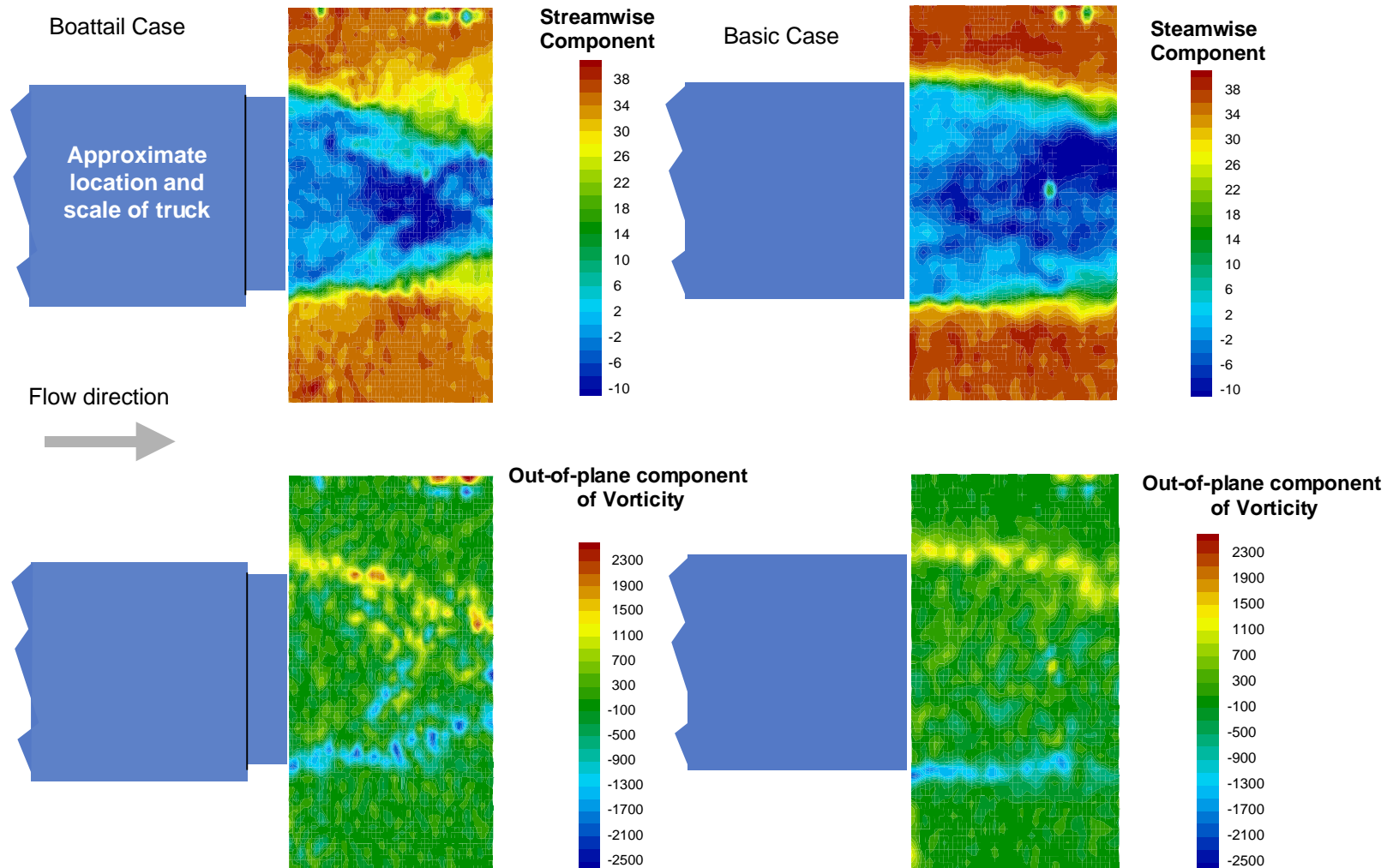
View upstream of test section with horizontal laser plane and camera orientation



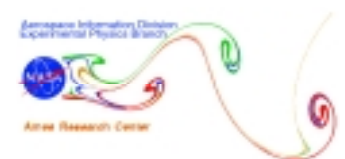


Horizontal plane at half-height, time averaged

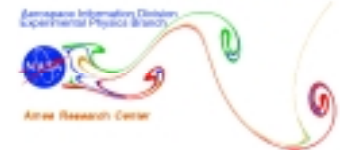
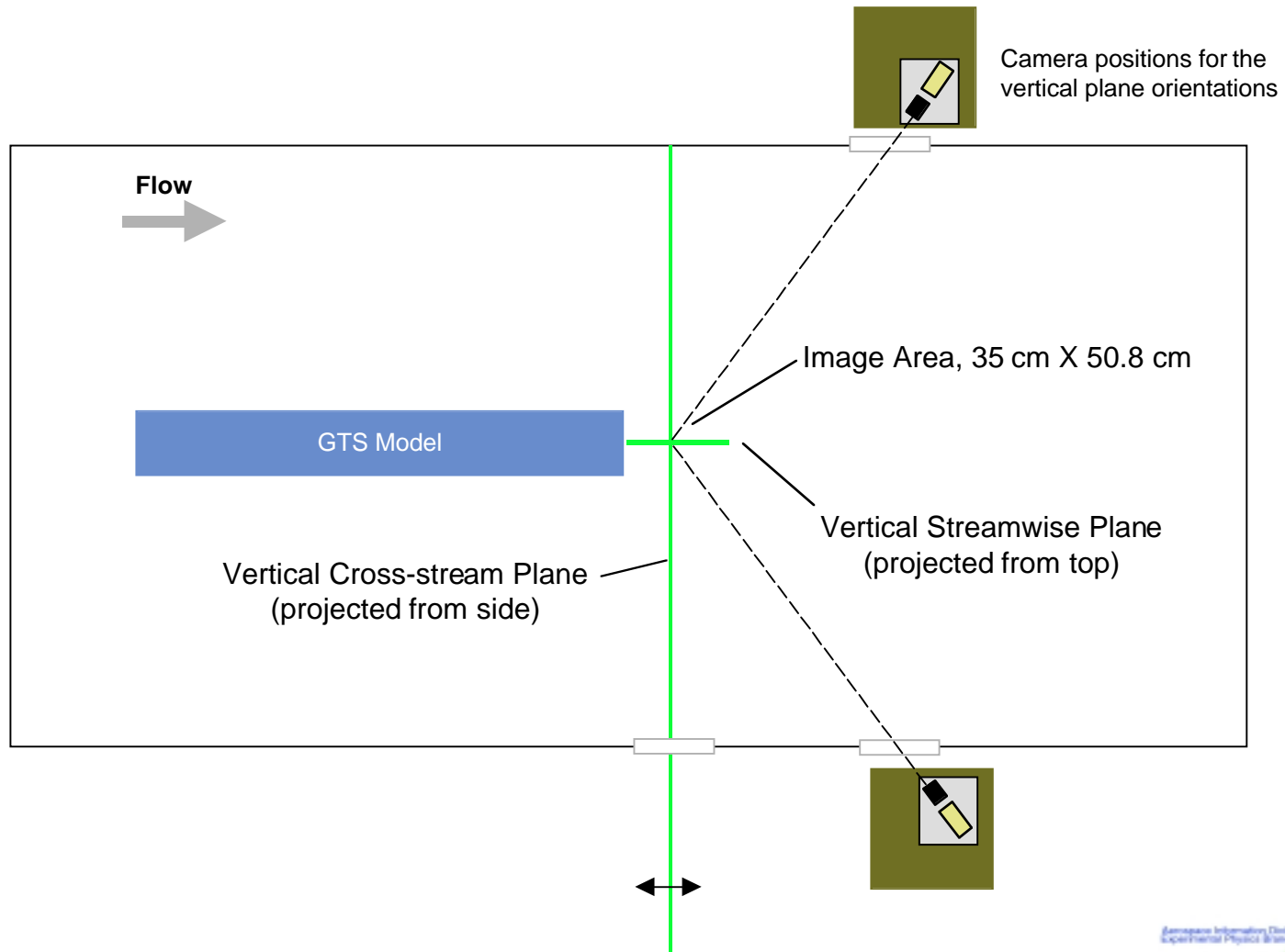


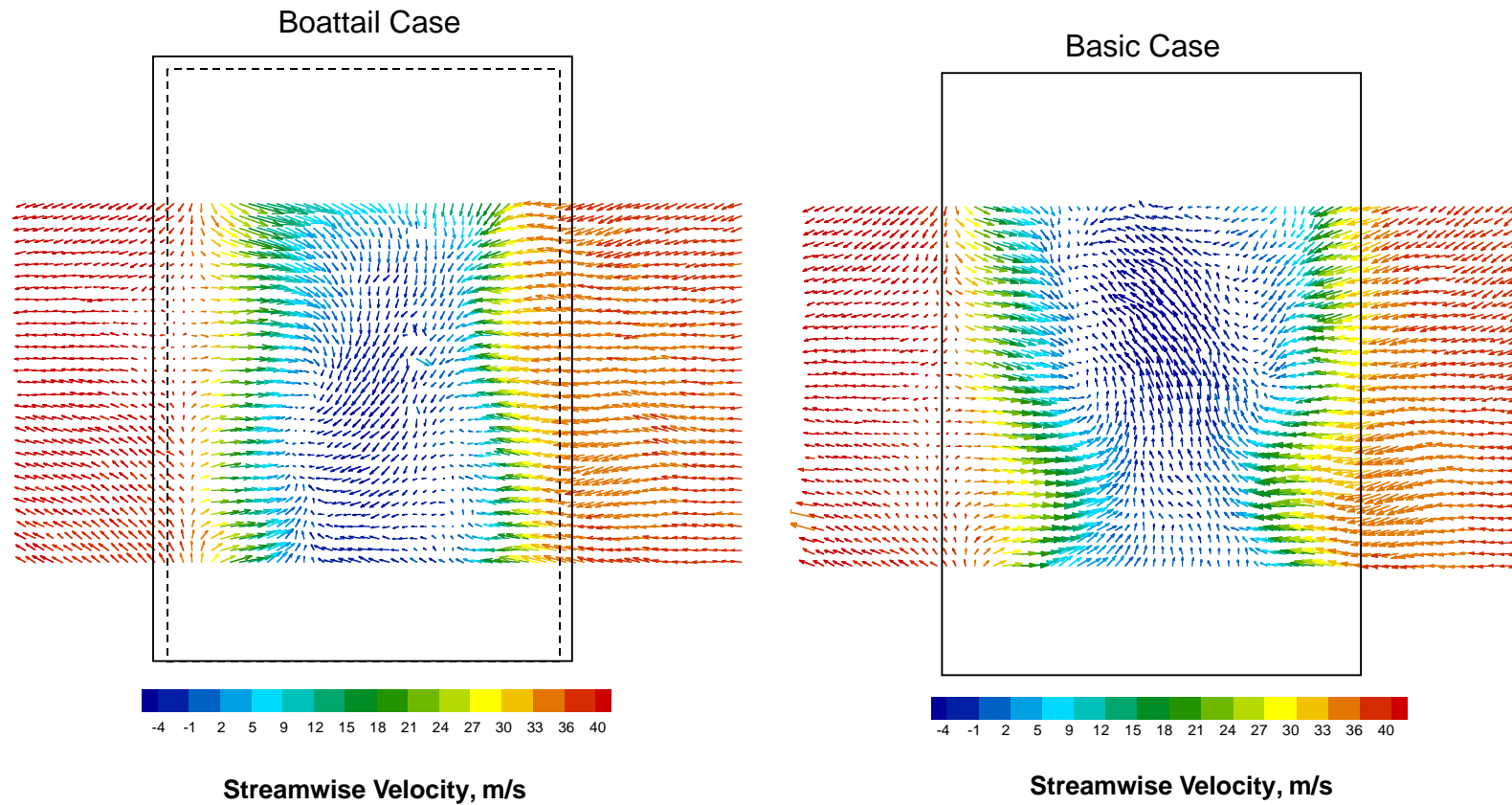


Horizontal plane at half-height, one measurement

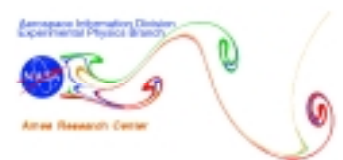


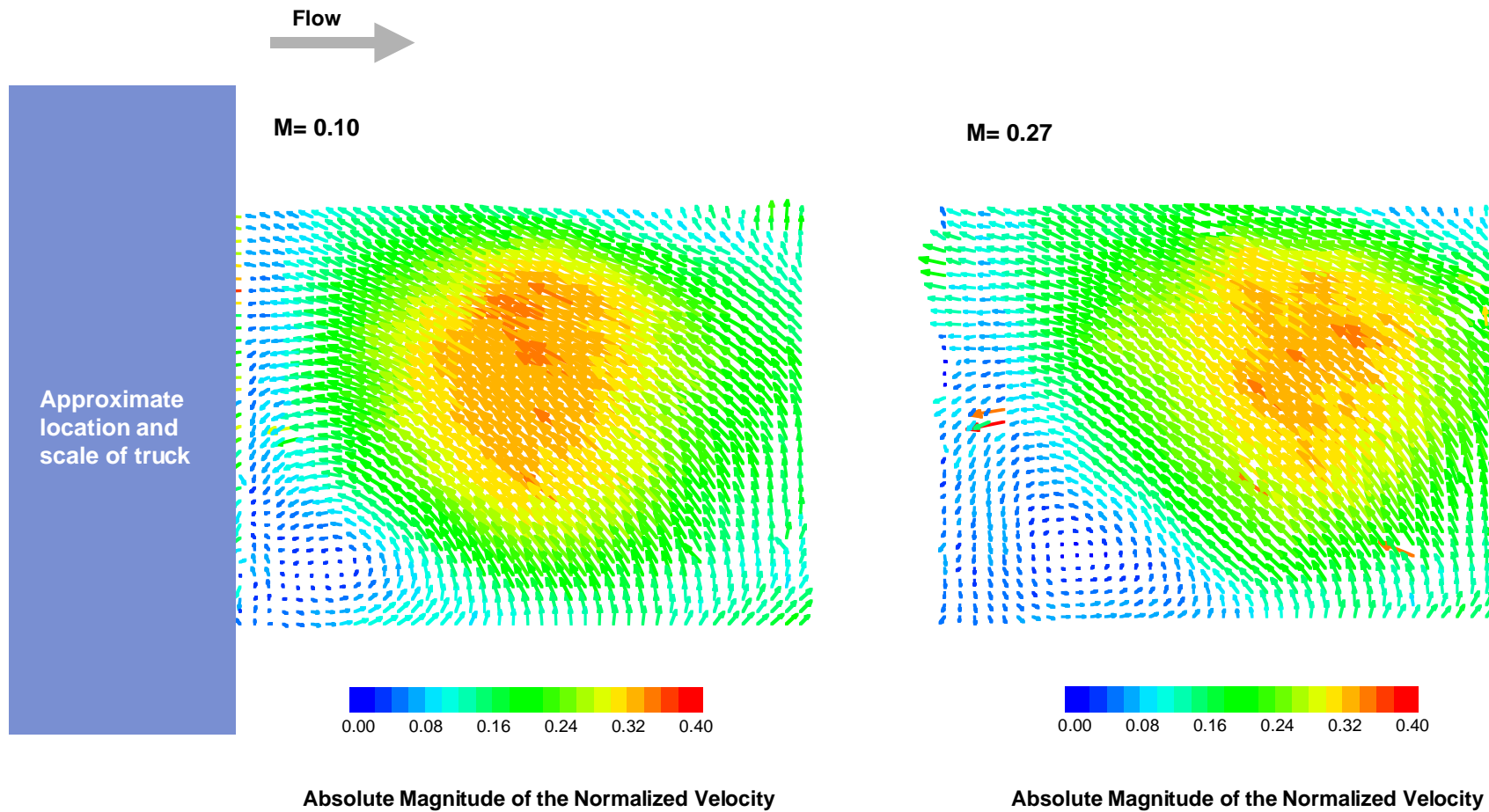
## Test Section - top view



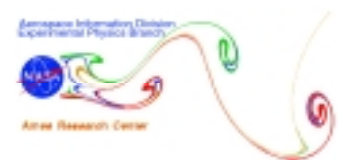


Cross-stream plane at 0.2 truck-lengths, time averaged

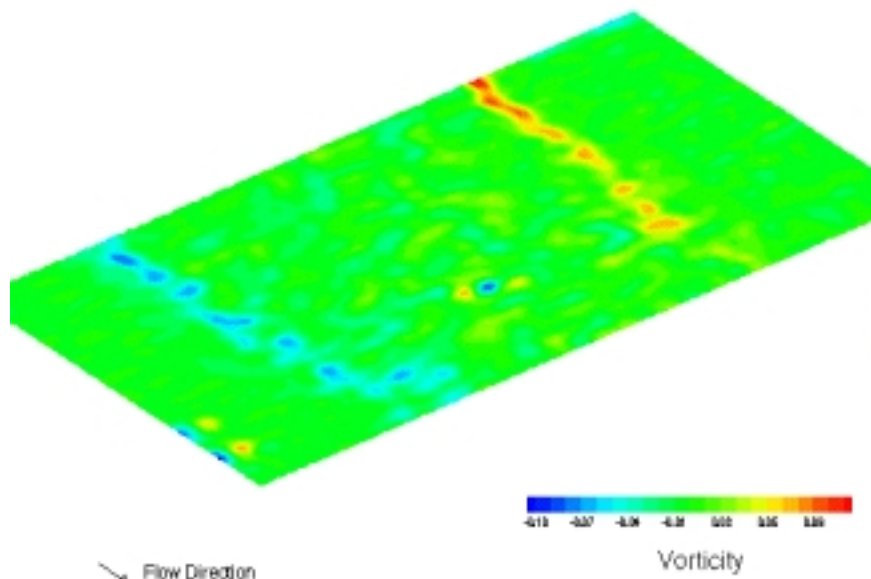




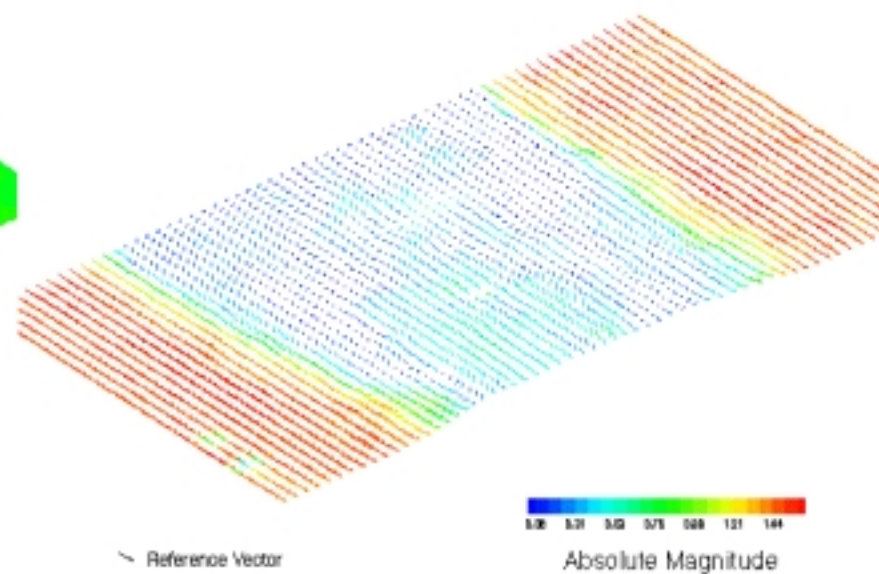
Steamwise plane at midwidth, time averaged



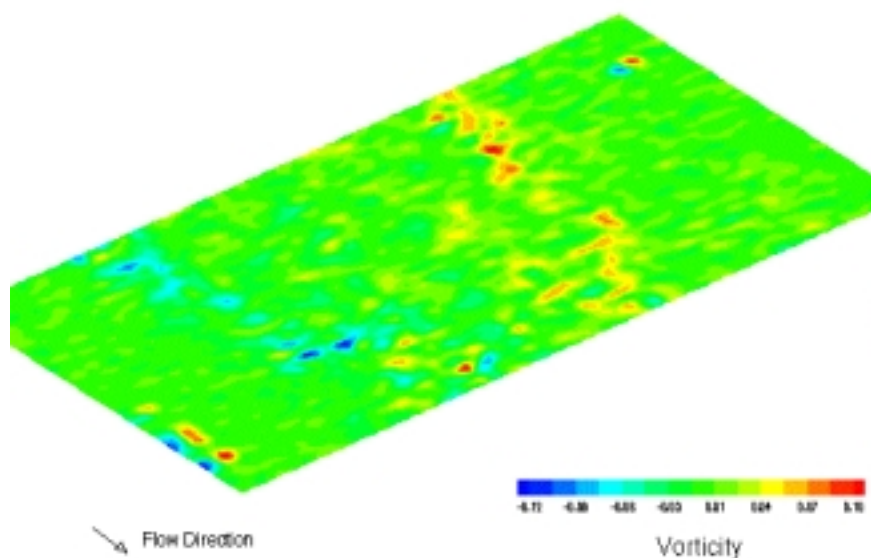
Basic Truck Case  
Horizontal Plane at Half Height



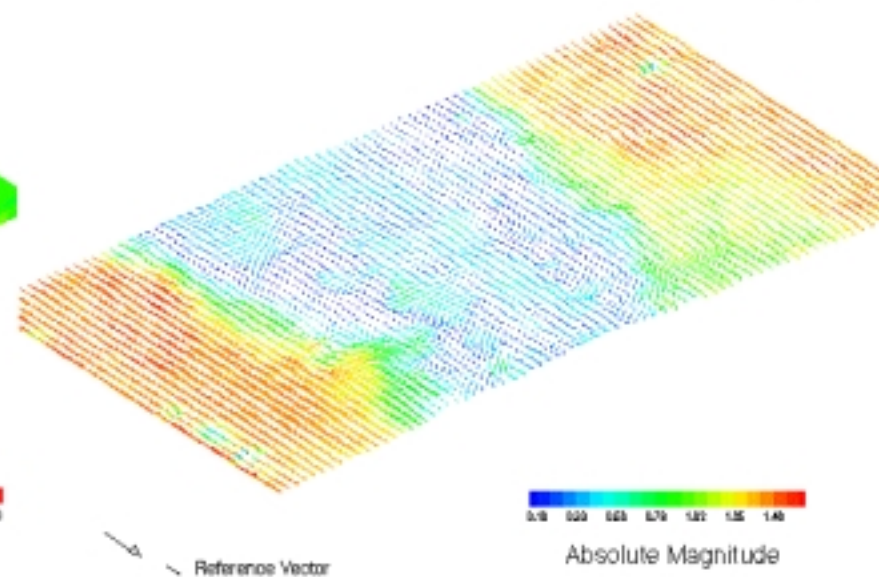
Basic Truck Case  
Horizontal Plane at Half Height



Boattail Case  
Horizontal Plane at Half Height

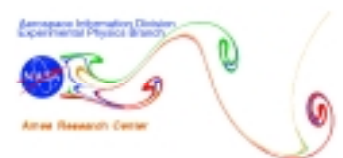


Boattail Case  
Horizontal Plane at Half Height



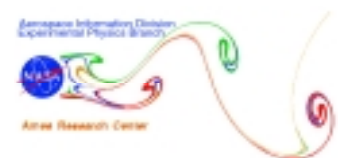
## Future Plans

- **Document experimental results**
  - NASA TM
  - SAE meeting paper
  - Post to internet
- **Test more realistic geometries**
  - Gap studies
  - Tractor details



## Summary

- **1/8-scale truck model tested in Ames 7x10**
- **Results show significant drag reduction with the addition of boattail plates**
- **Significant Reynolds number effect observed below  $Re = 1$  million**
- **Large data set available for CFD validation**





# **Computational Prediction of Aerodynamic Drag for a Simplified Truck Geometry**

**Kambiz Salari**

**Walter H. Rutledge**

**Aerosciences and Compressible Fluid Mechanics Department**

**Sandia National Laboratories**

**SAE International Truck and Bus Meeting and Exposition**

**November 14, 1999**



## Outline

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- **Sandia Ground Transportation System (GTS) project history (including TAMU experiment)**
- **Approaches to flow simulations**
- **Issues with computational boundary conditions**
- **RANS simulations for TAMU experiment**
  - Different yaw angles ( $0^\circ$  &  $10^\circ$ )
- **Ongoing Efforts**
- **Concluding Remarks**



# Acknowledgement

---

## **Sandia Ground Transportation System (GTS) Project (1993-1996)**

**Walter T. Gutierrez**

**Basil Hassan**

**Robert H. Croll**

**Jose E. Suazo**

**Mary A. McWherter-Payne**

**Walter P. Wolfe**



# Ground Transportation System (GTS) Baseline Geometry

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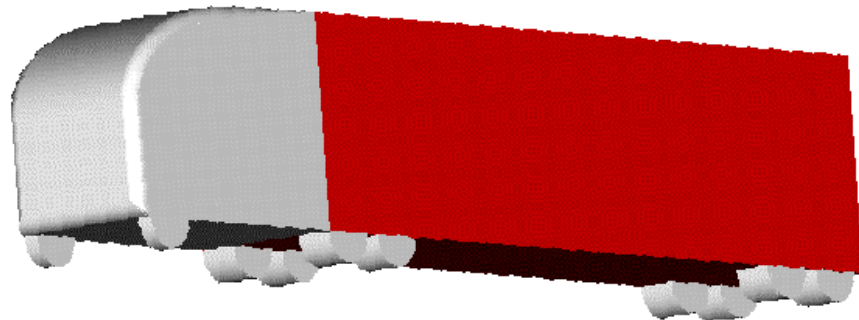
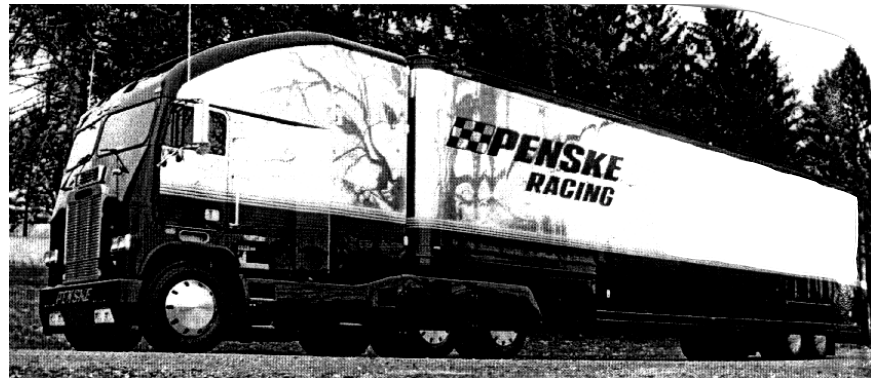
Project had two parts:

- Experimental (TAMU)
- Computational

## Cab-Over Tractor-Trailer

For simplicity

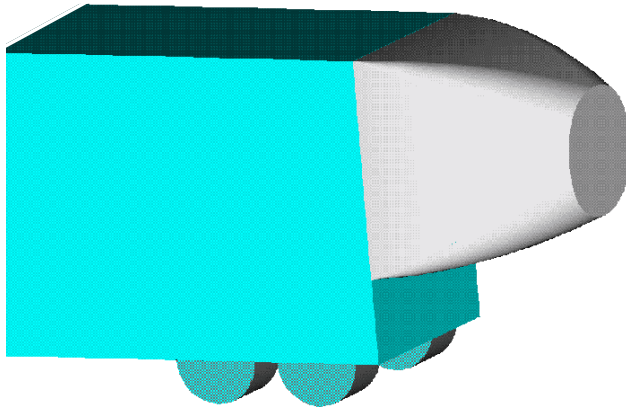
- Mirrors,
- Wheel wells,
- Tractor-trailer gap,  
not simulated.





## Add-on Geometries: Ogives and Slants

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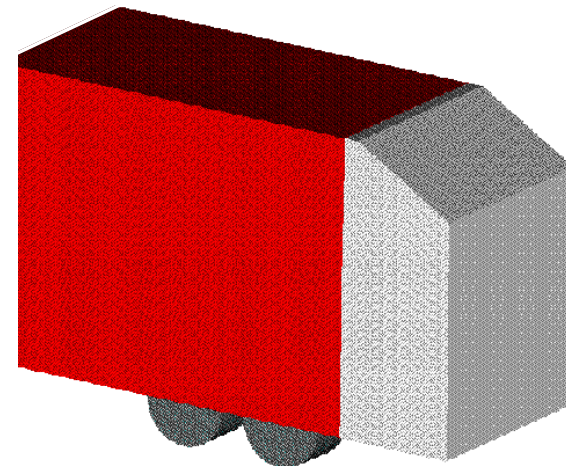


### Ogival Boattails

- 1.5 m (5 ft) and 2.4 m (8 ft) long
- Tangent at top of trailer and sides
- Blend from square to circle
- Primarily boundary layer separation

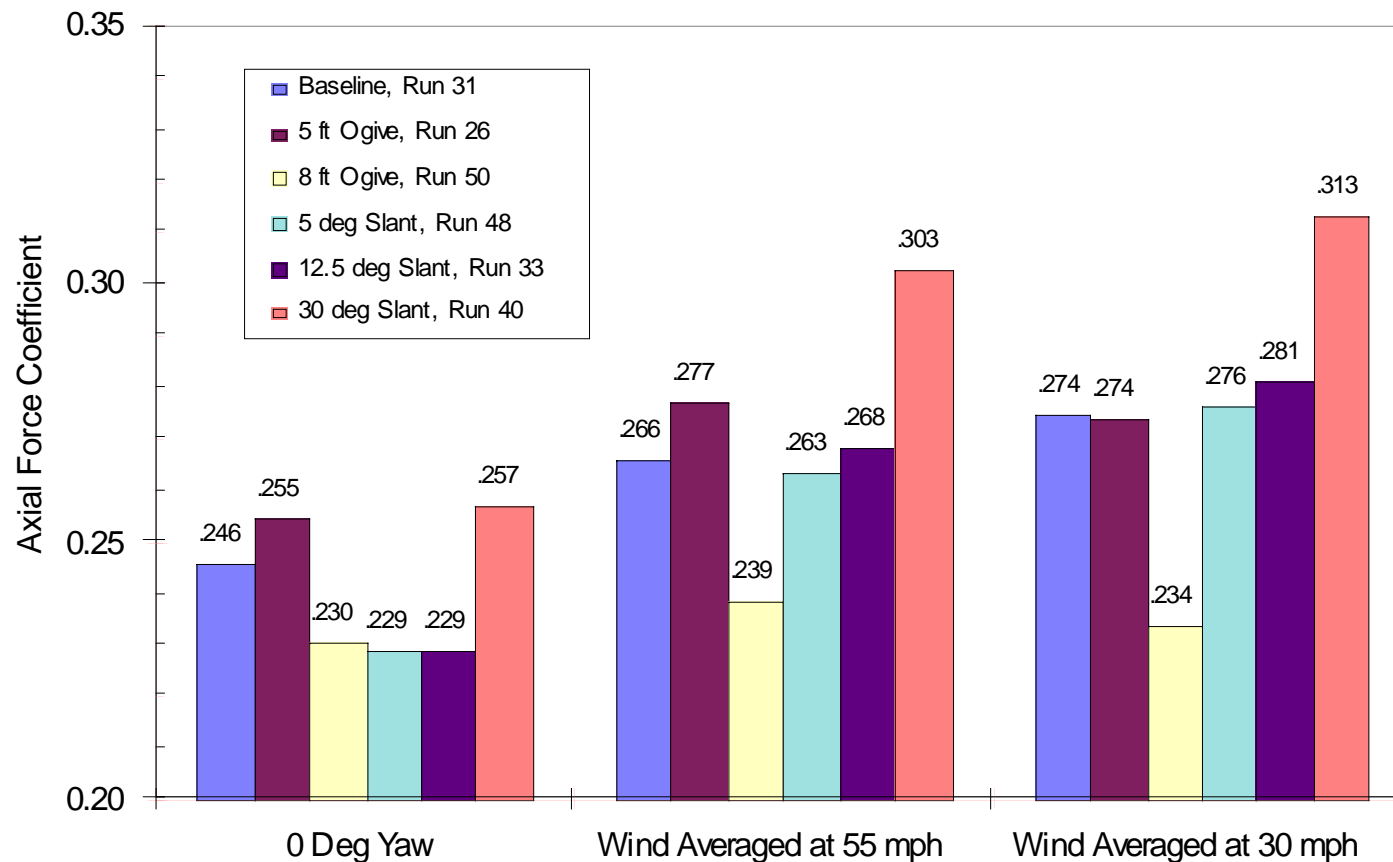
### Slants

- 5, 12.5, and 30 fastbacks
- Scaled from work by Ahmed, et al.
- Primarily boundary layer separation and vortex interaction





# Axial Force “Drag” Coefficient Texas A&M Experiment





# **Sandia Computational Approach**

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## **Simulation of Flow Field Around Heavy Vehicles**

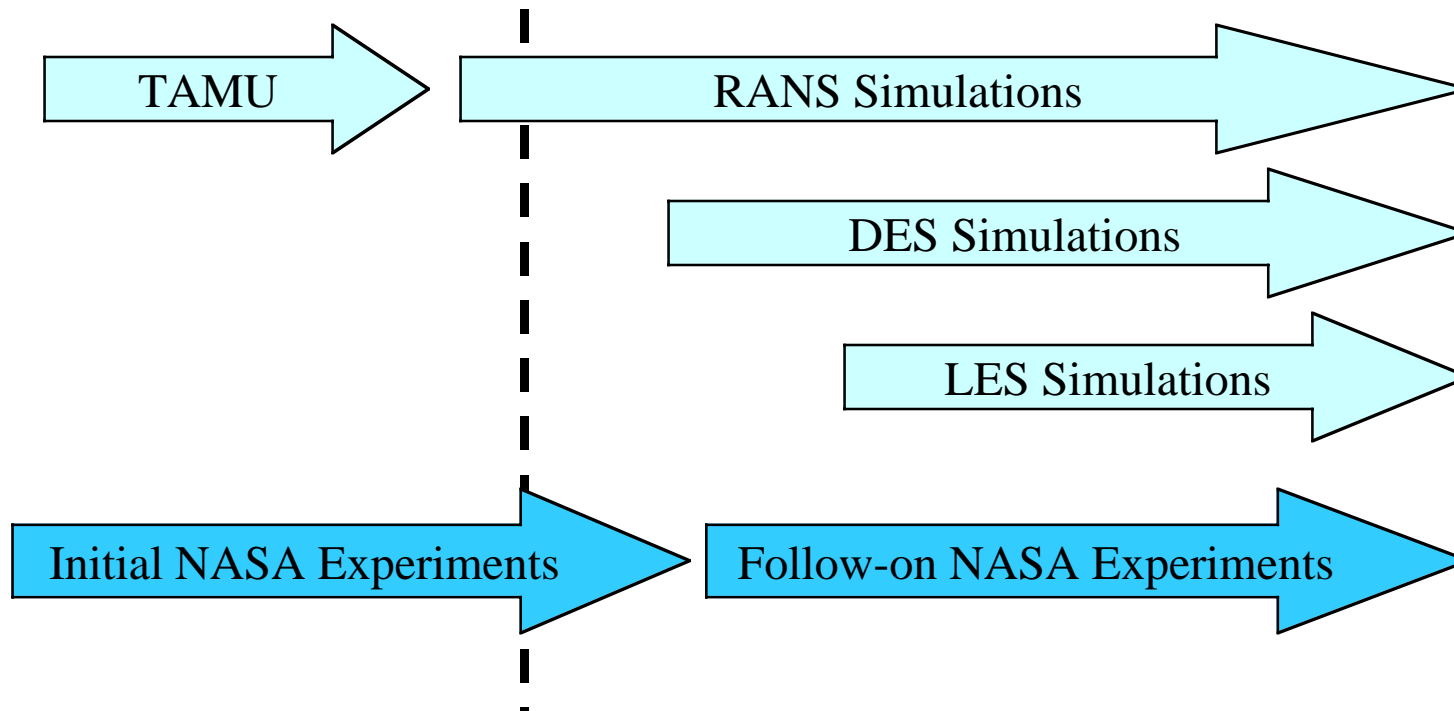
- **Reynolds Averaged Navier-Stokes (RANS)**
- **Detached Eddy simulations (DES)**
- **Large Eddy simulations (LES)**



## Sandia Computational Approach, Cont.

---

11/14/99





# SACCARA Code Capabilities

Sandia Advanced Code for Compressible Aerothermodynamics Research and Analysis

- Multi-block, structured grids for 2-D, Axisymmetric, and 3-D flows
- Solution of the Full Navier-Stokes equations for compressible Flows
- Finite volume spatial discretization (steady and unsteady)
- MP implementation on a variety of distributed parallel architectures (IBM, Intel, etc.)
- Implicit time advancement schemes
- Subsonic → Hypersonic flows
- Zero-, one-, and two-equation turbulence models
- Ideal, equilibrium, and thermo-chemical nonequilibrium finite-rate gas chemistry
- Rotating coordinate system





## SACCARA Code Capabilities, Cont.

---

**SACCARA is a Modern Navier-Stokes Code**

The code can be executed on range of computing platforms, such as, high-end PC, single workstation, parallel workstation clusters, and MP machines.

The code has **comprehensive plan** for Verification & Validation.



# Computational Boundary Conditions

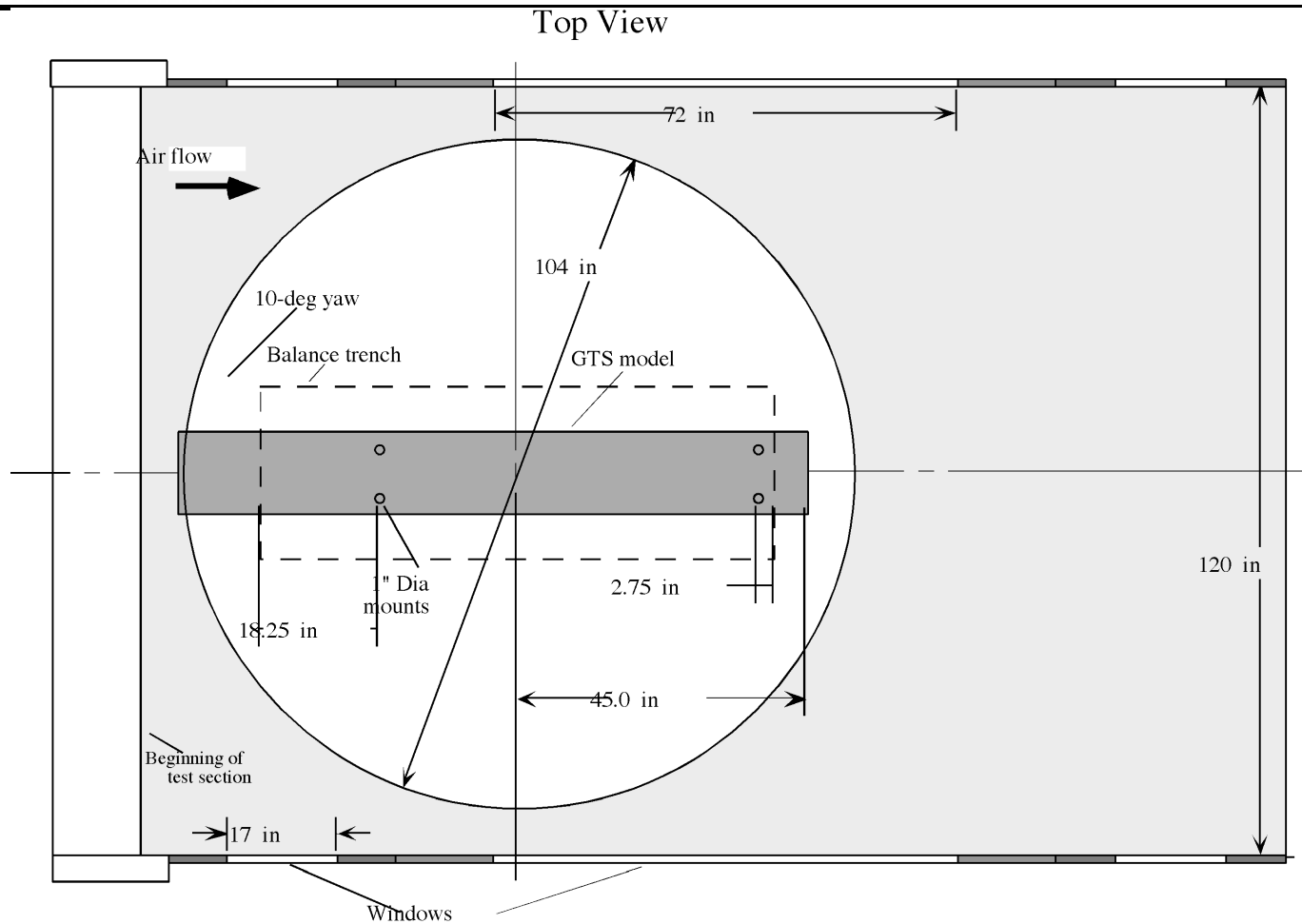
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## Modeling Wind Tunnel Experiment

- **Inflow**
  - Boundary layer profile
  - Uniformity of the incoming flow
  - Description of turbulent fluctuations (intensities)
- **Outflow**
- **Far Field boundary**
- **Modeling tunnel walls (blockage)**

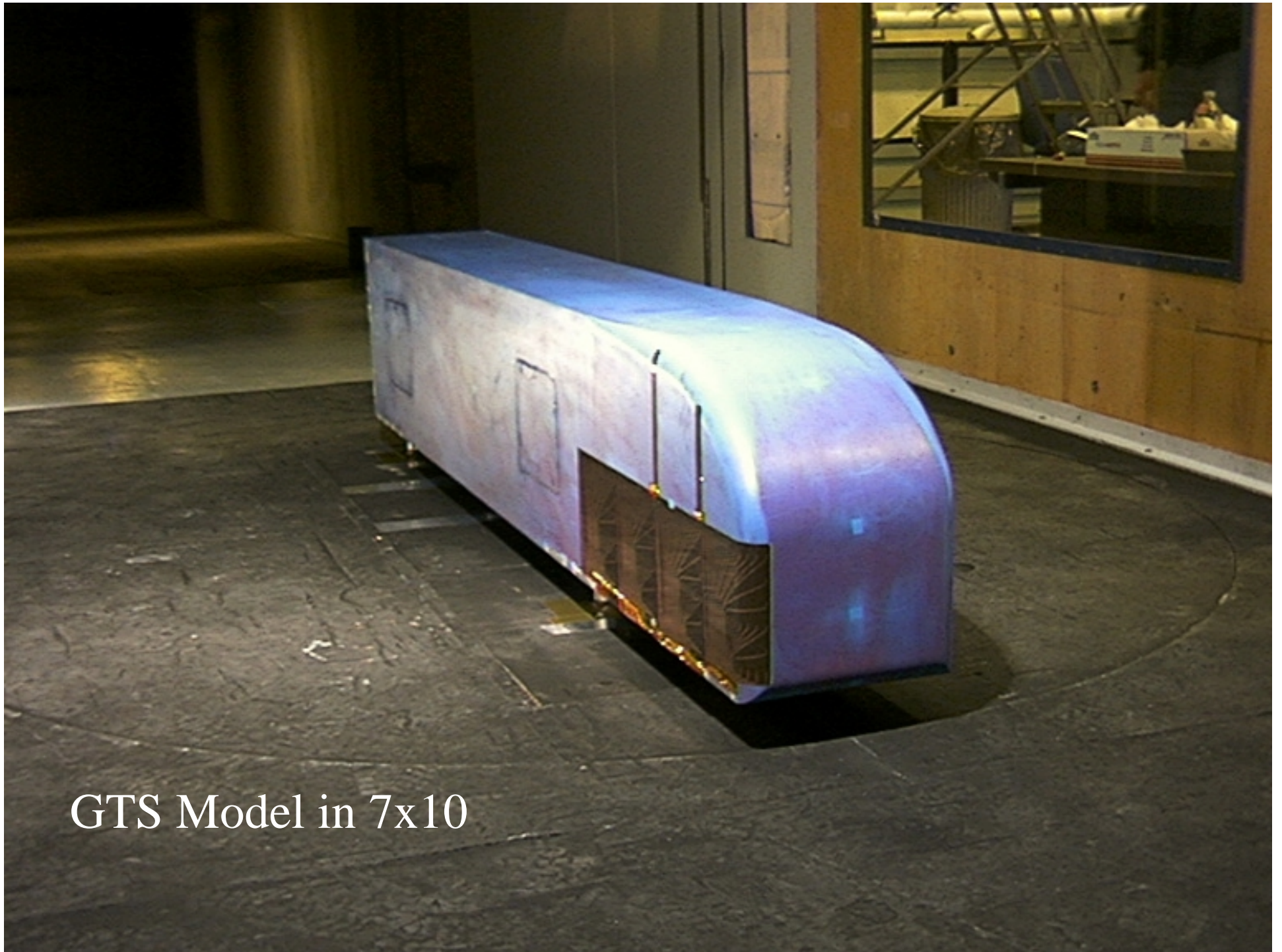


# GTS Model Installation at NASA 7'x10'



GTS Model: Ames 7x10 Installation

Scale: 1" = 1.75'



GTS Model in 7x10



# **GTS Flow Simulation, Texas A&M Test**

---

## **Test Condition for run 31, no wheels:**

**$Re = 1.6 \times 10^6$**

**Yaw angle =  $0^\circ$  and  $10^\circ$**

**Free stream velocity = 78 (m/s)**

**Free stream Mach number = 0.23**

**Density =  $1.17 \text{ (kg/m}^3\text{)}$**

**Static Pressure = 99,470.6 (Pa)**

**Kinematic viscosity =  $1.555 \times 10^{-5} \text{ (m}^2\text{/s)}$**

**Reference: Robert H. Croll, Walter T. Gutierrez, Basil Hassan, Jose E. Suazo and Anthony J. Riggins, "Experimental Investigation of the Ground Transportation Systems (GTS) Project for Heavy Vehicle Drag Reduction," SAE Paper 960907, 1996.**



## Matrix for Grid Convergence Study

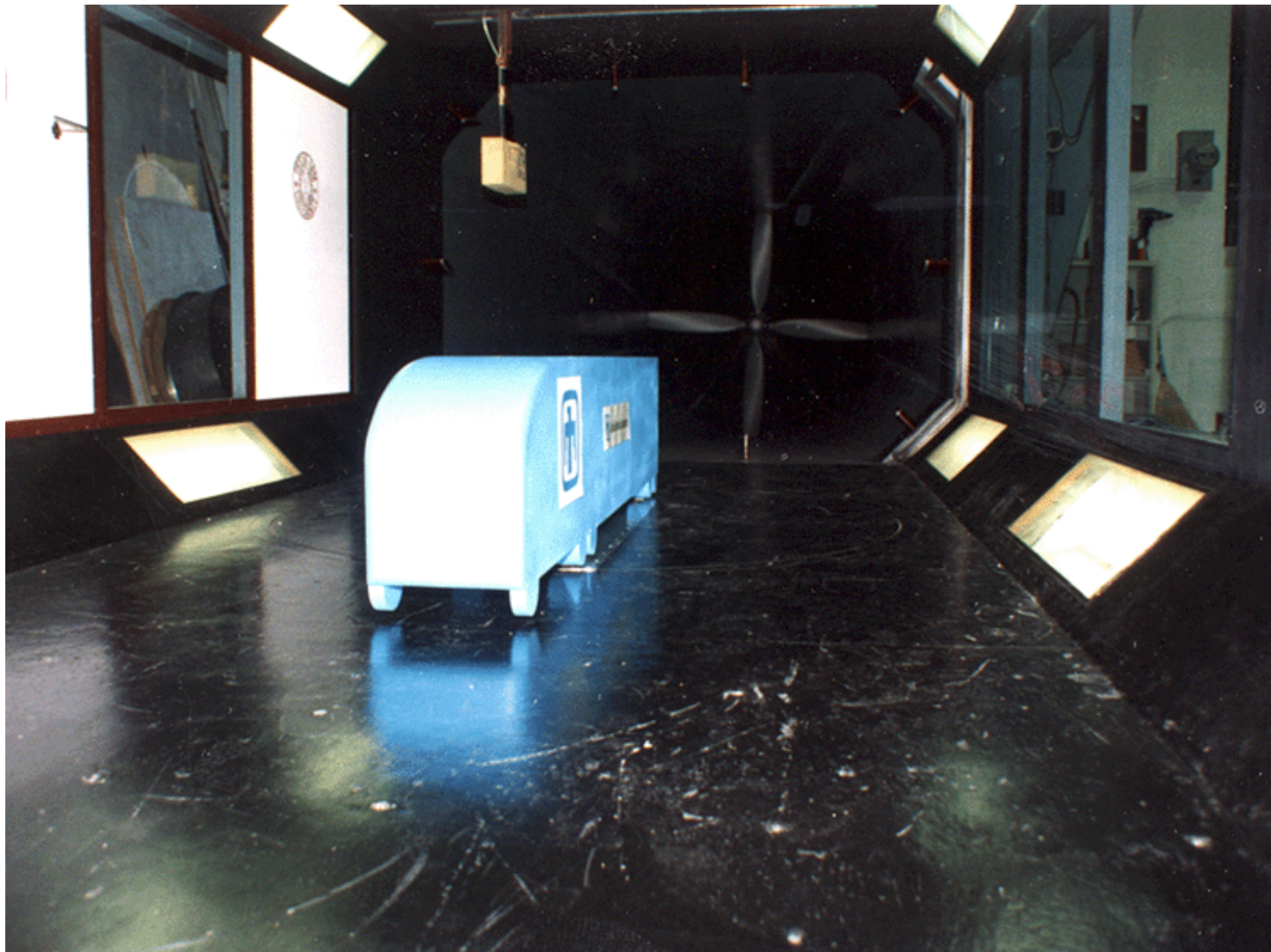
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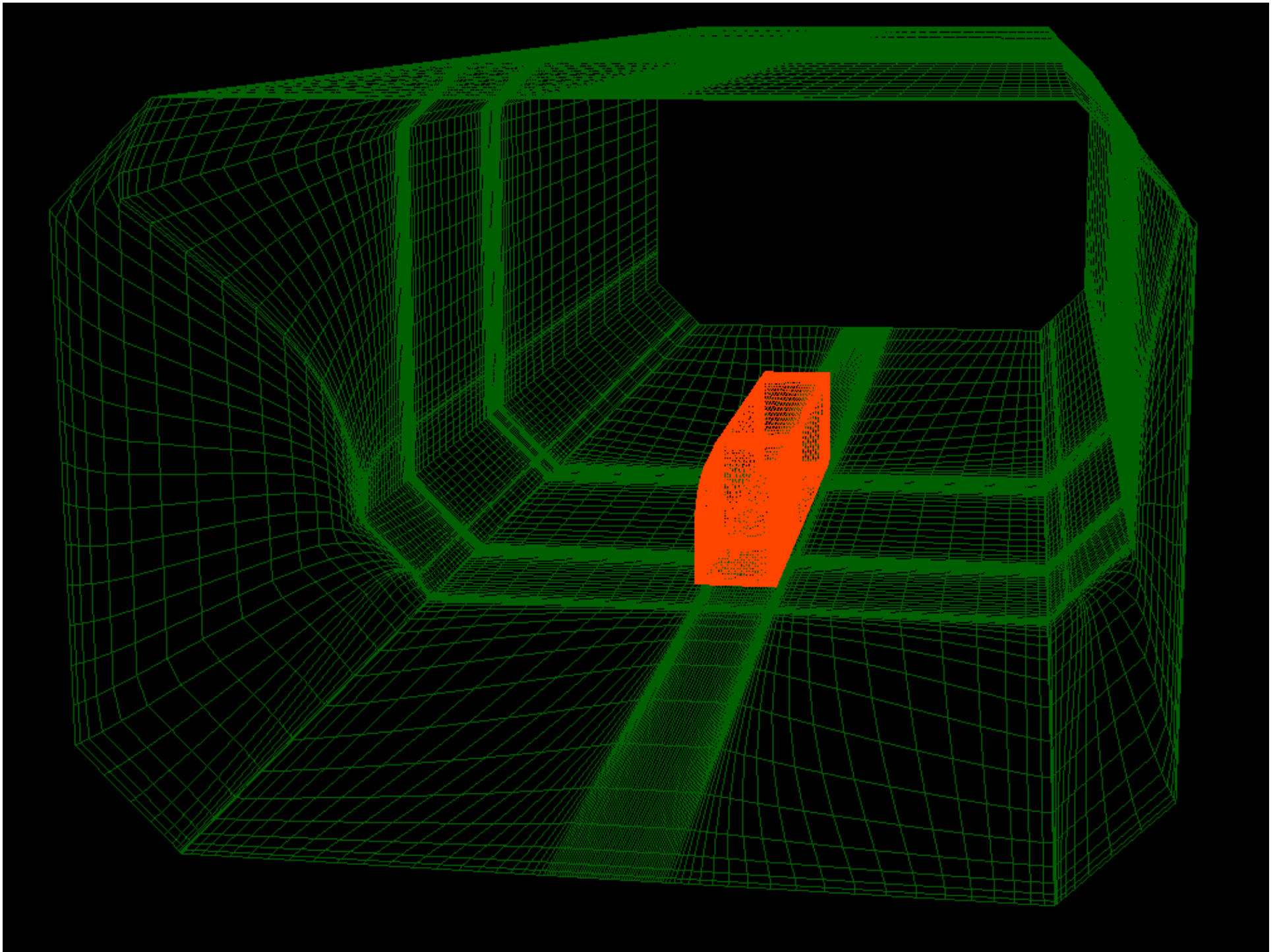
Yaw Angle	Grid Size		
	Coarse	Medium	Fine
0	X	X	In Progress
10	X	X	In Progress

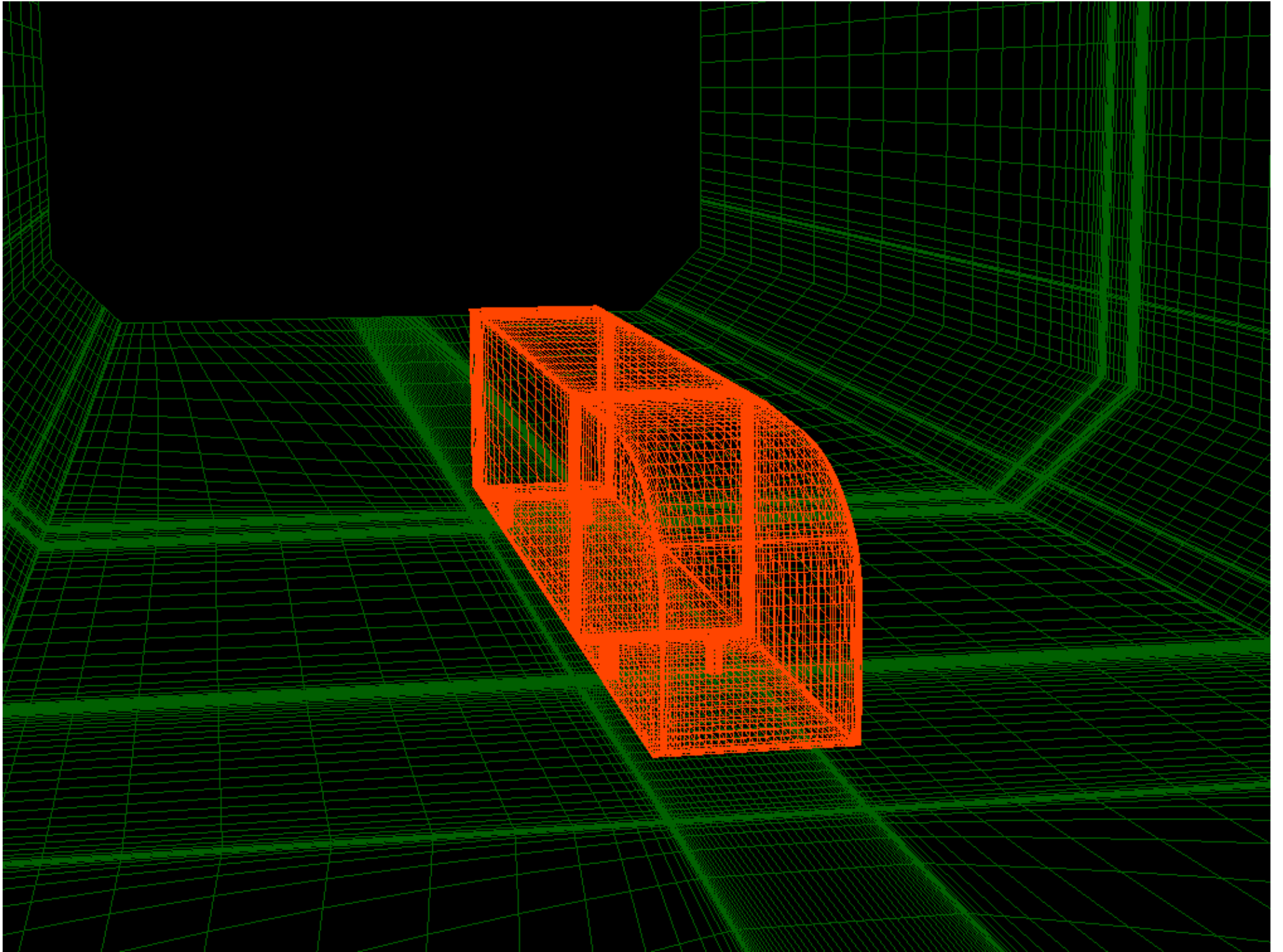
**Coarse Mesh: 0.5 million nodes, 107 processors**

**Medium Mesh: 4 million nodes, 246 processors**

**Fine Mesh 32 million nodes, 1400 processors**



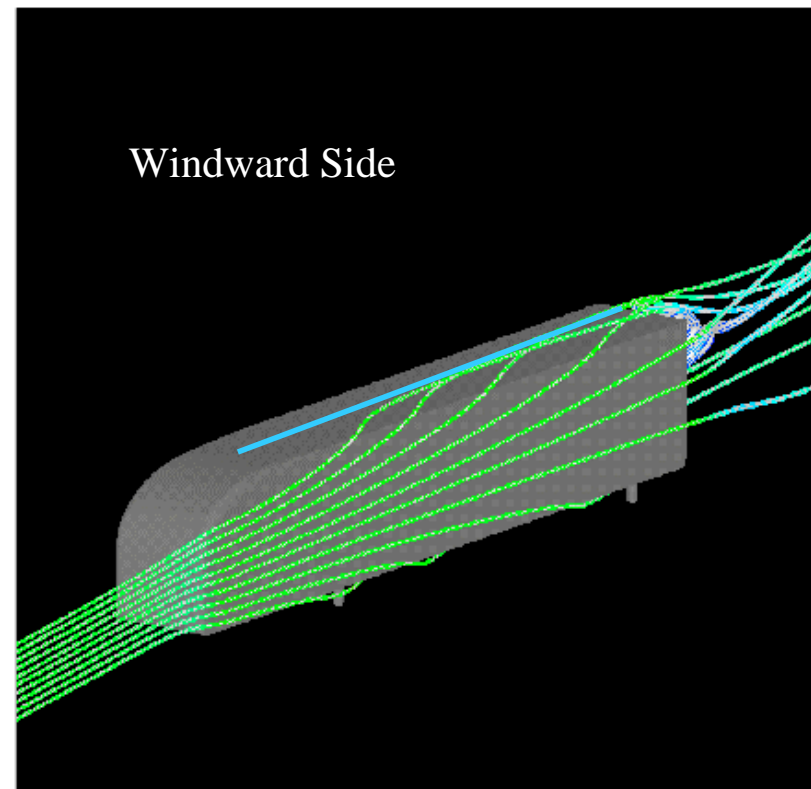
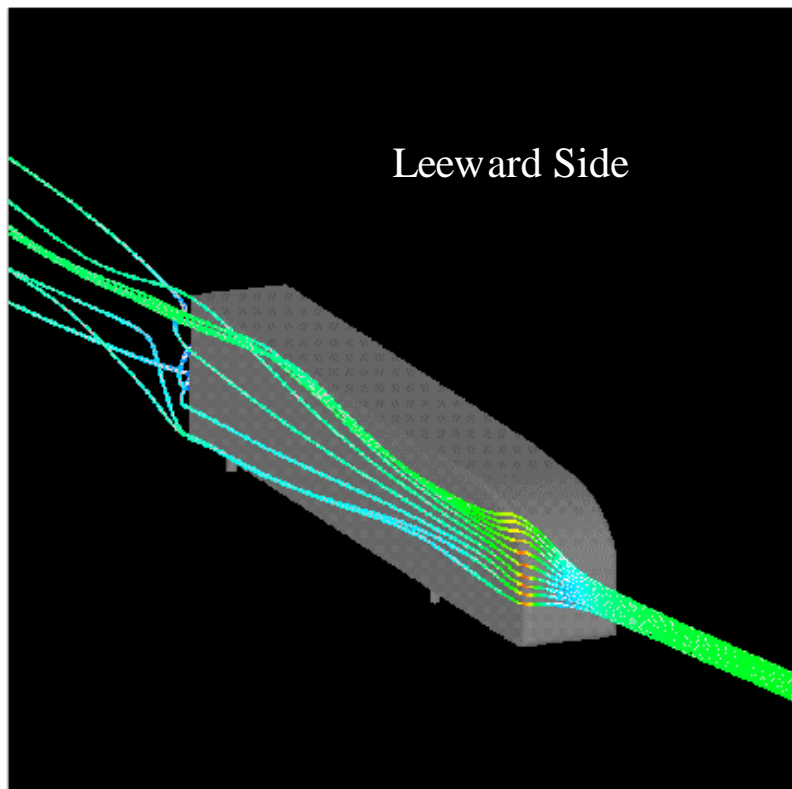






## GTS Flow Simulation

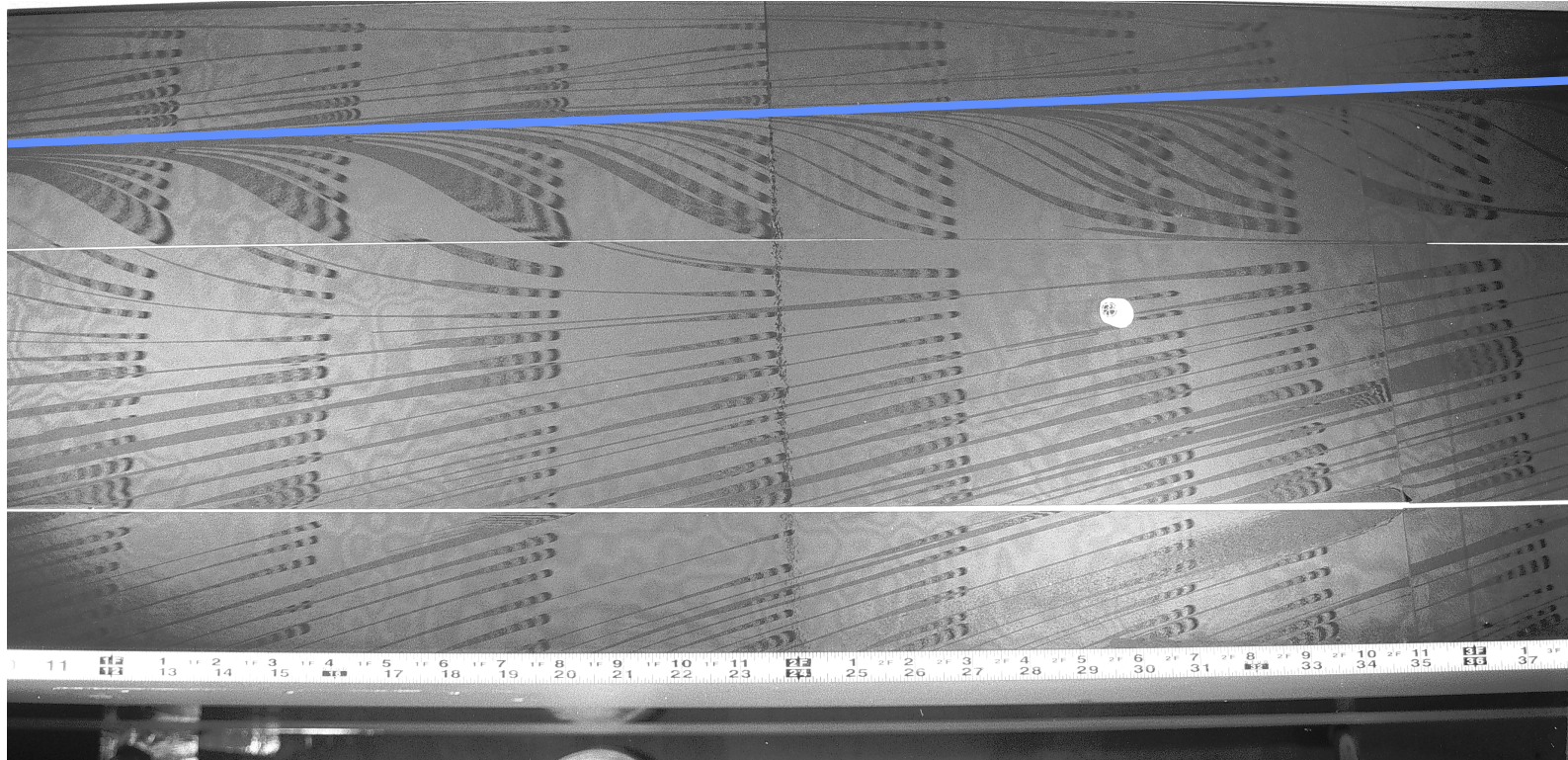
10° yaw, Medium mesh, Particle traces are colored by velocity magnitude





## Oil Film Image

Top view of trailer at  $10^\circ$  yaw



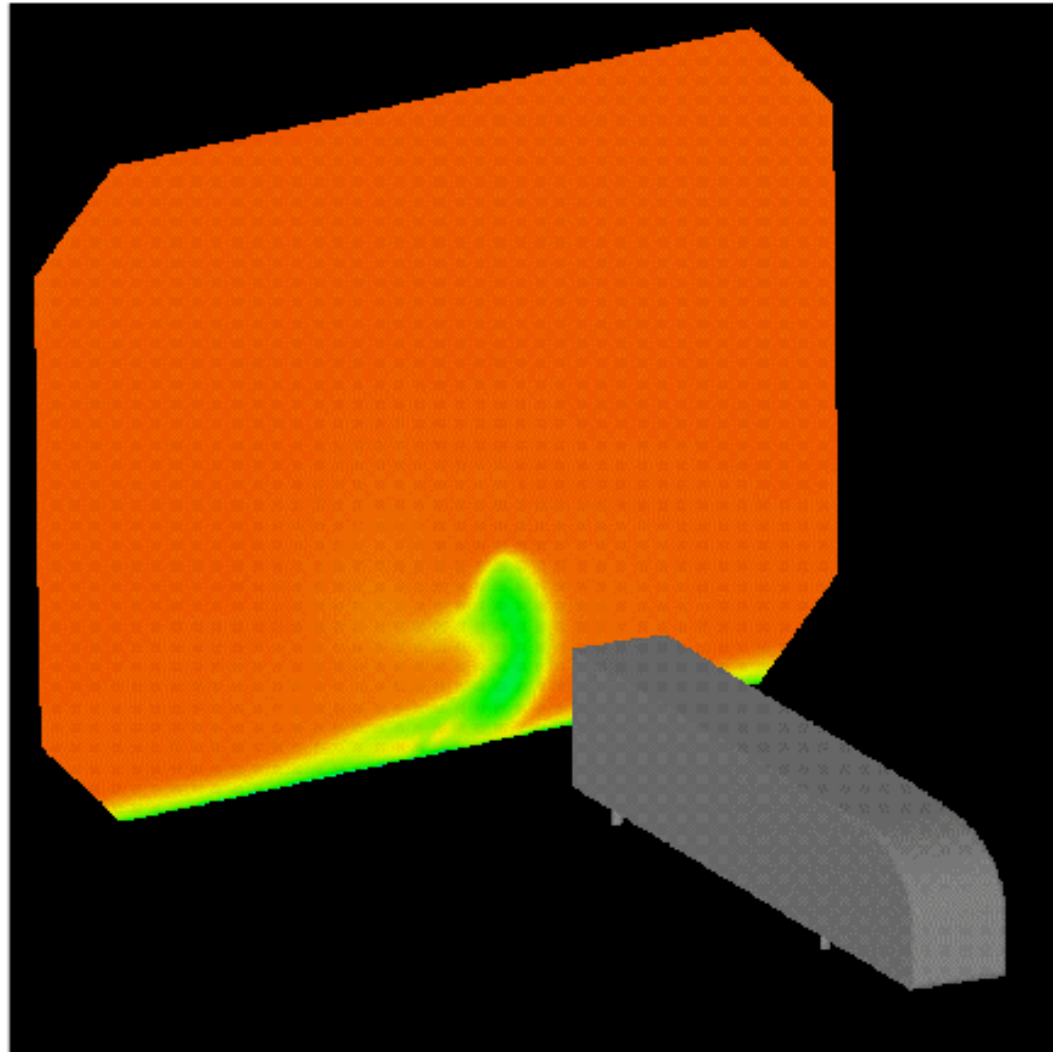
Skin friction is proportional to fringe spacing



# GTS Flow Simulation

---

10° yaw  
x-plane cut  
Mach contours





# GTS Flow Simulation

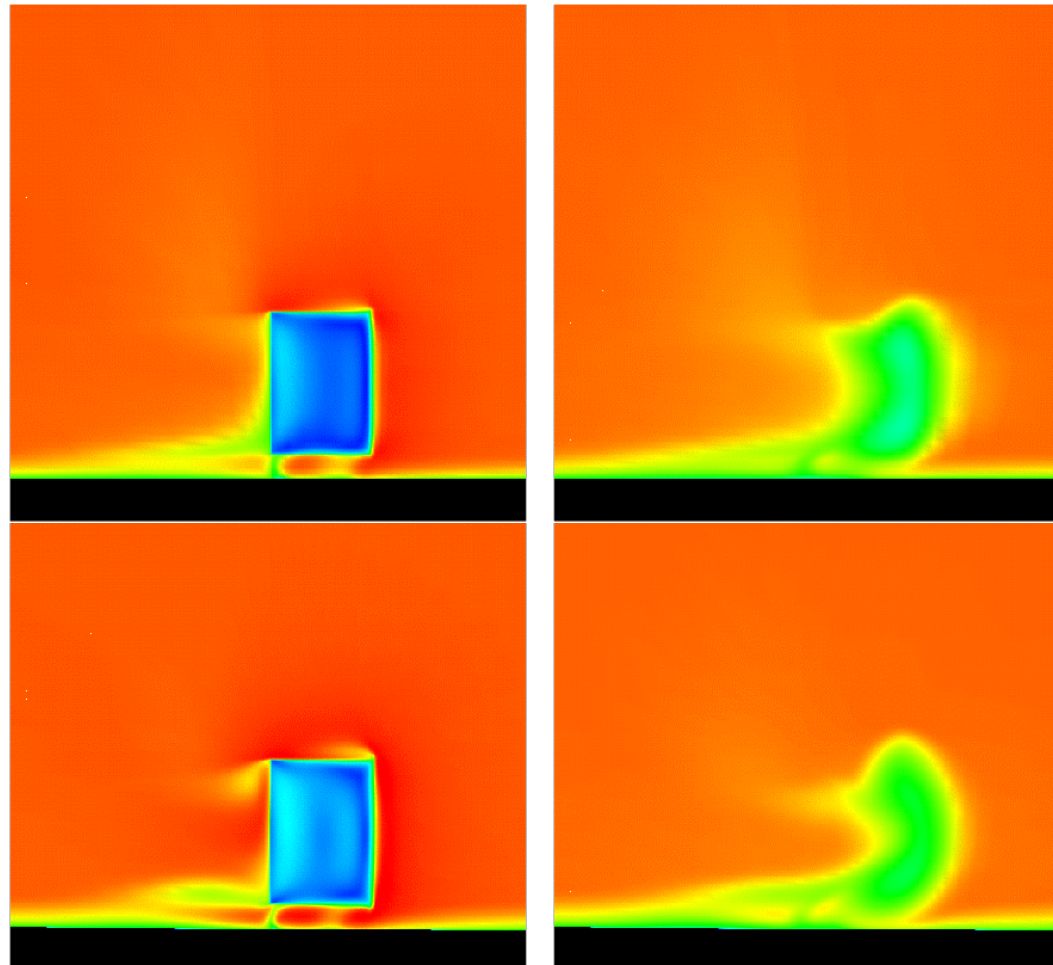
10° yaw  
x-plane cut  
Mach contours

Coarse

Medium

$x = 2.5 \text{ m}$

$x = 3.25 \text{ m}$

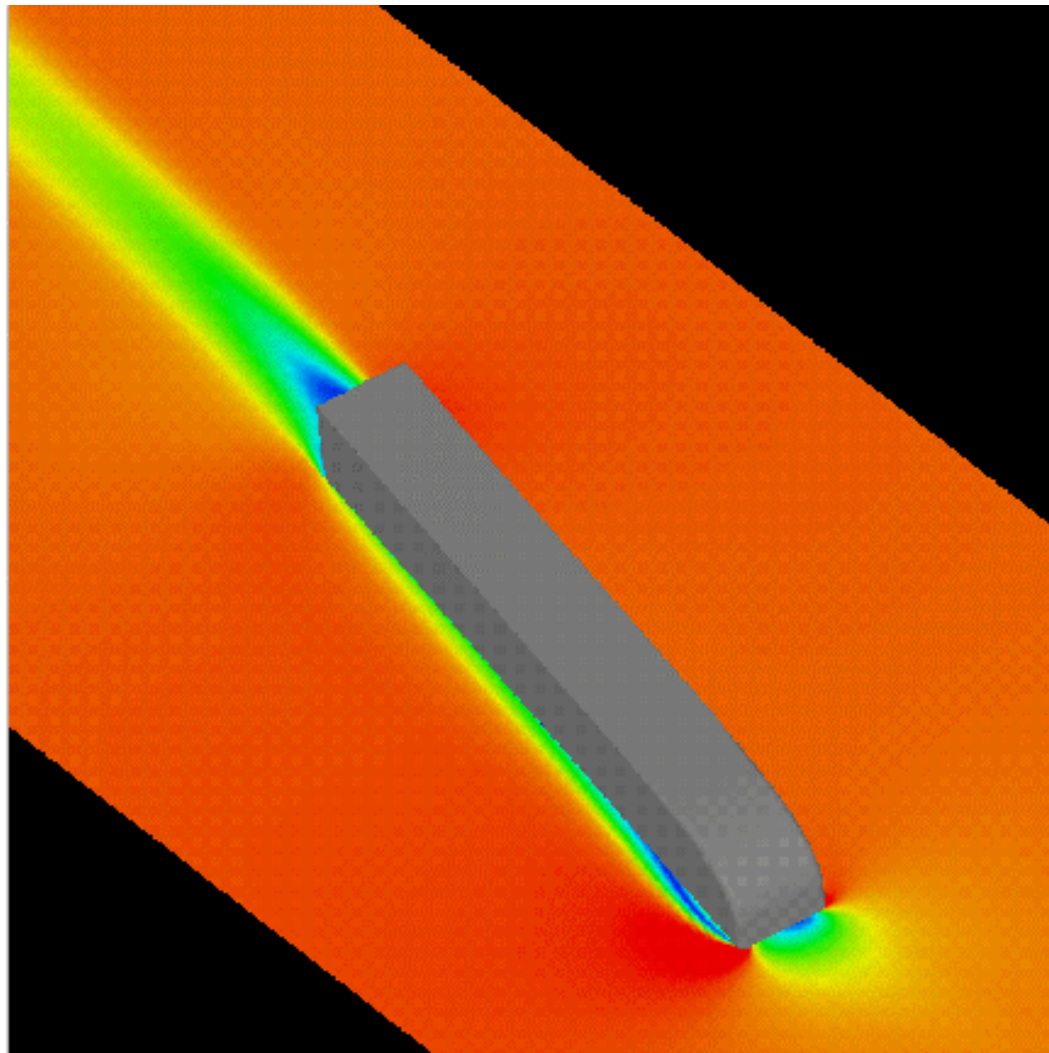




# GTS Flow Simulation

---

10° yaw  
y-plane cut  
Mach contours





# GTS Flow Simulation

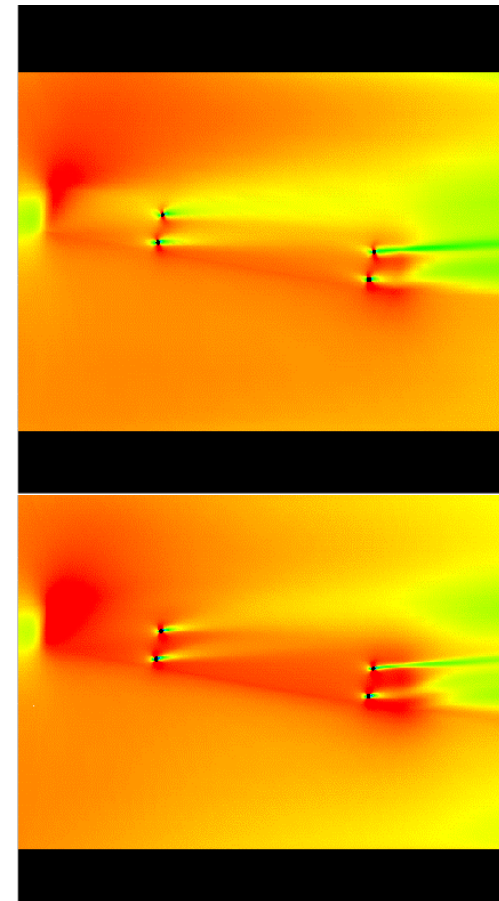
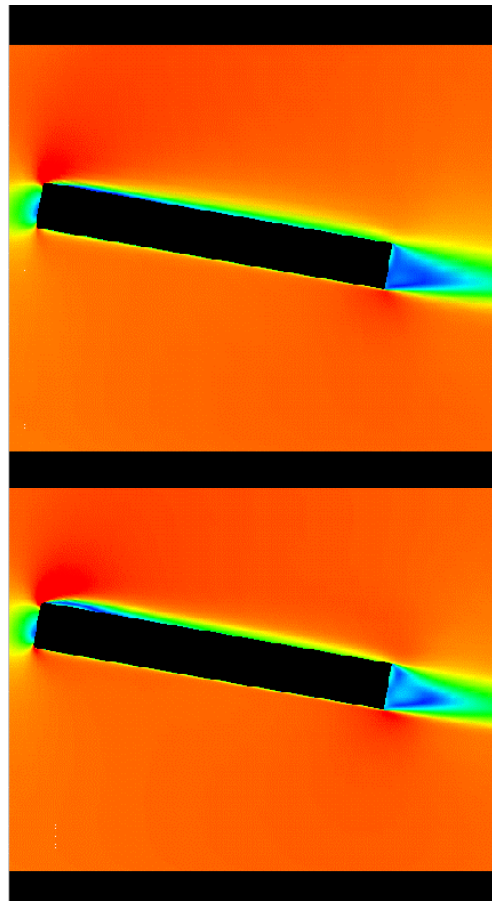
10° yaw  
y-plane cut  
Mach contours

$y = 0.122 \text{ m}$

$y = -0.035 \text{ m}$

Coarse

Medium

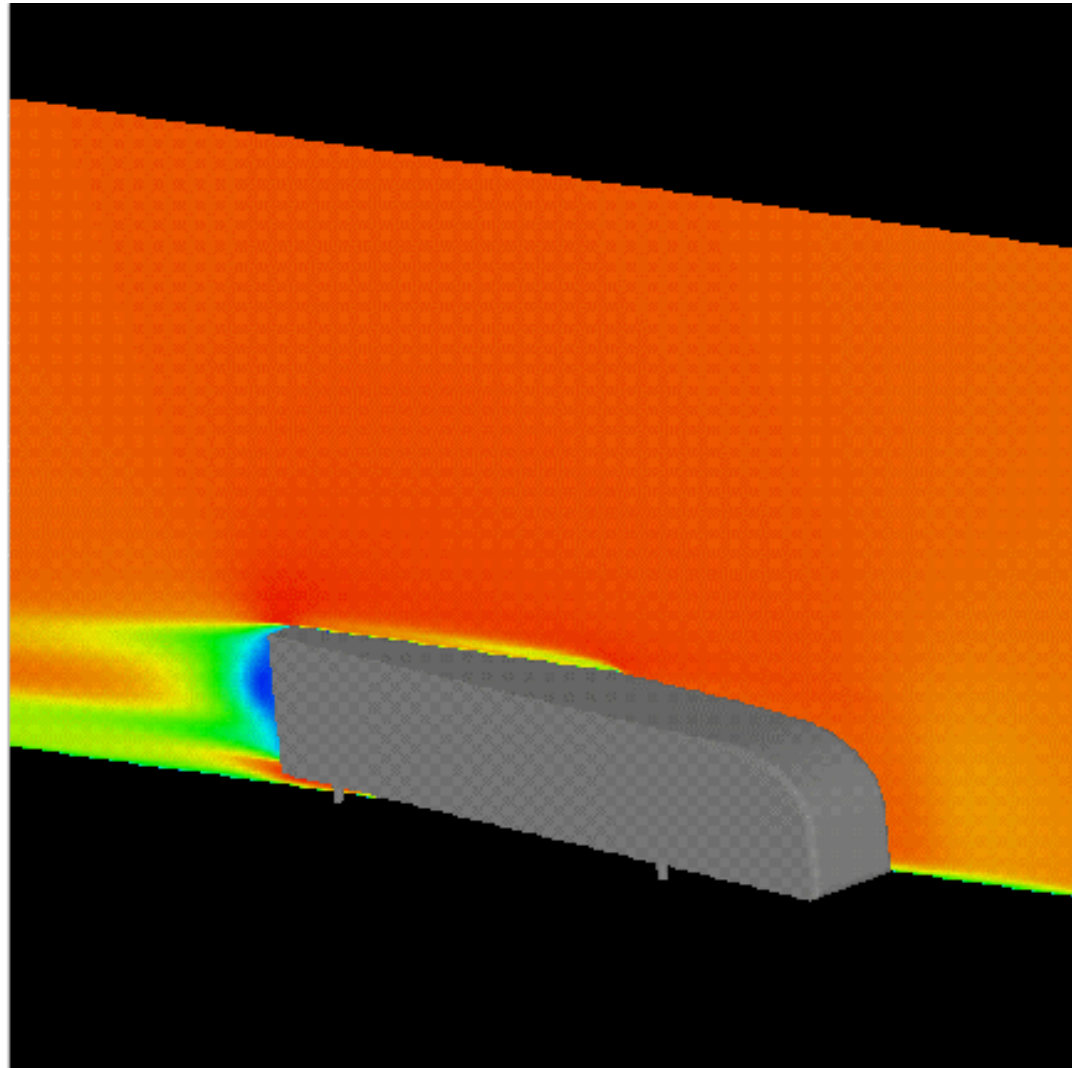




# GTS Flow Simulation

---

10° yaw  
z-plane cut  
Mach contours





# GTS Flow Simulation

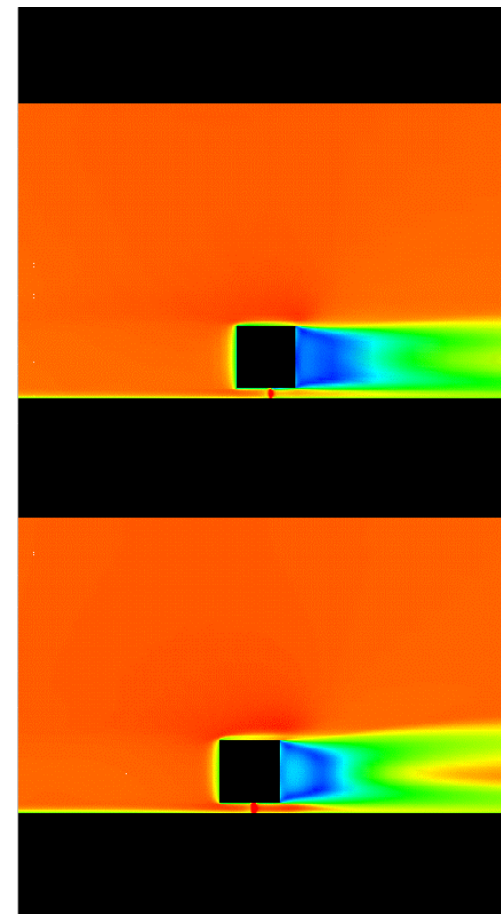
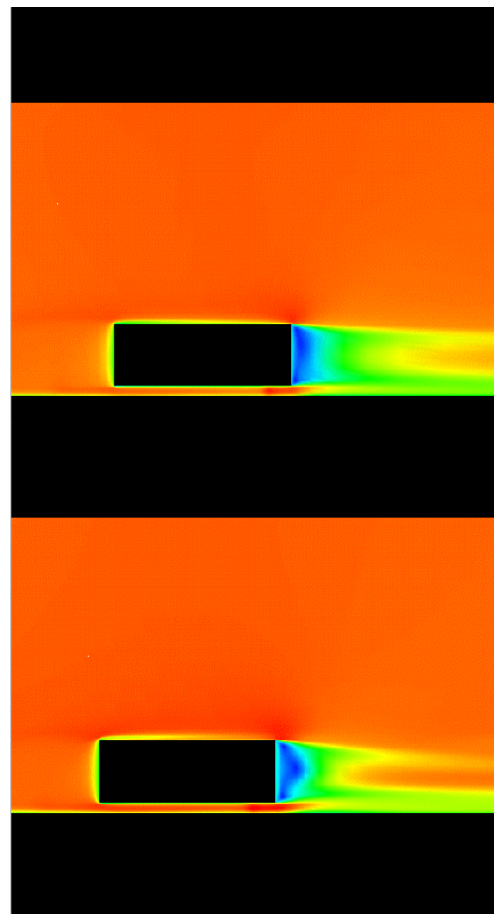
10° yaw  
z-plane cut  
Mach contours

$z = 0.07 \text{ m}$

$z = 0.215 \text{ m}$

Coarse

Medium

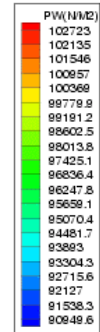
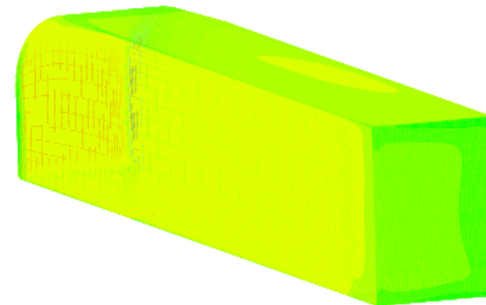
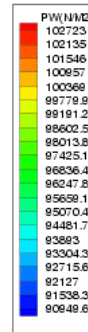
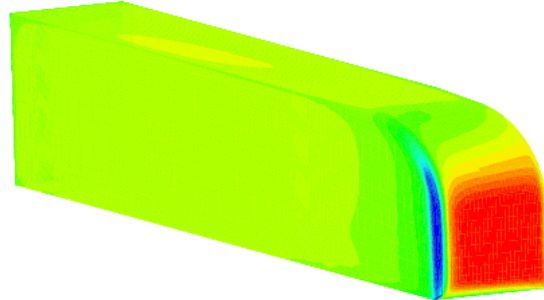




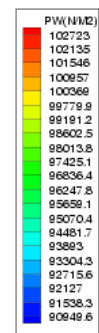
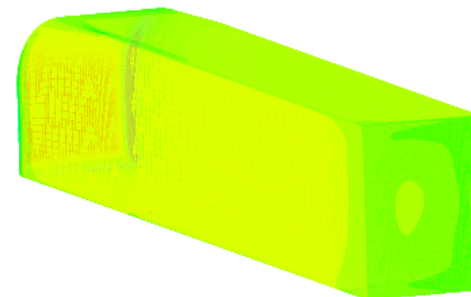
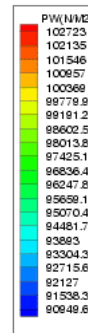
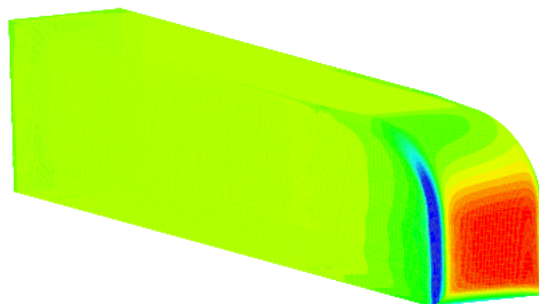
# Pressure Distribution on the Surface

10° yaw

Coarse



Medium

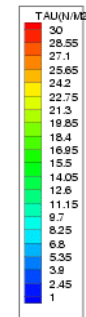
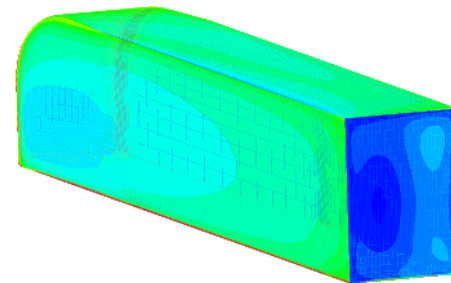
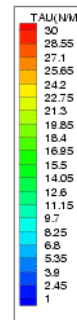
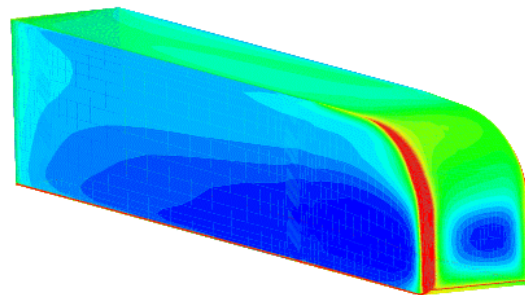




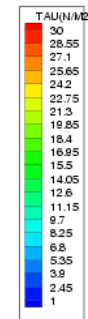
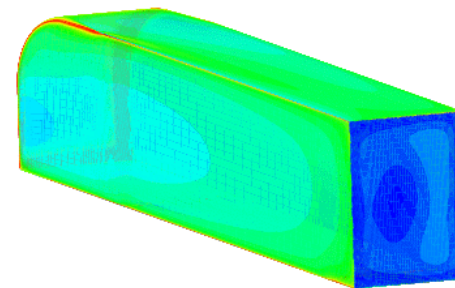
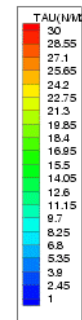
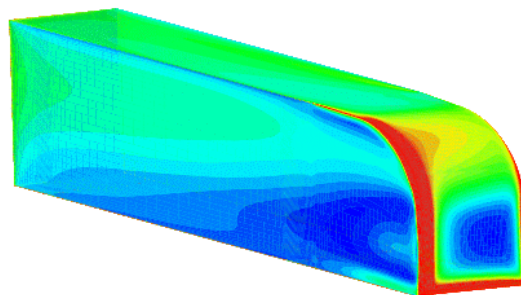
# Shear Stress Distribution on the Surface

10° yaw

Coarse



Medium



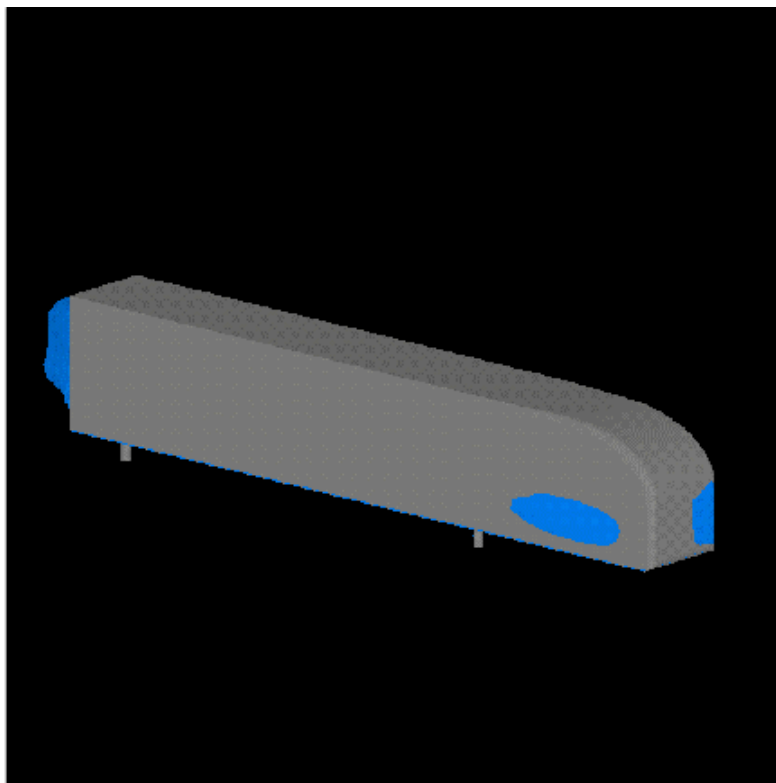


# GTS Flow Simulation

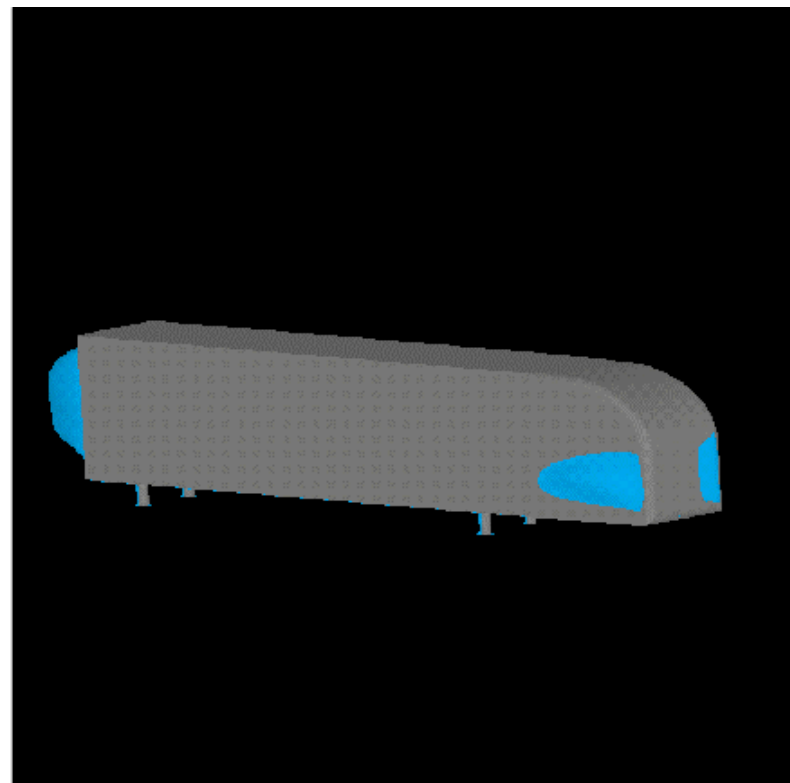
---

10° yaw, IsoSurface  $u = -0.001$  (m/s)

Coarse



Medium

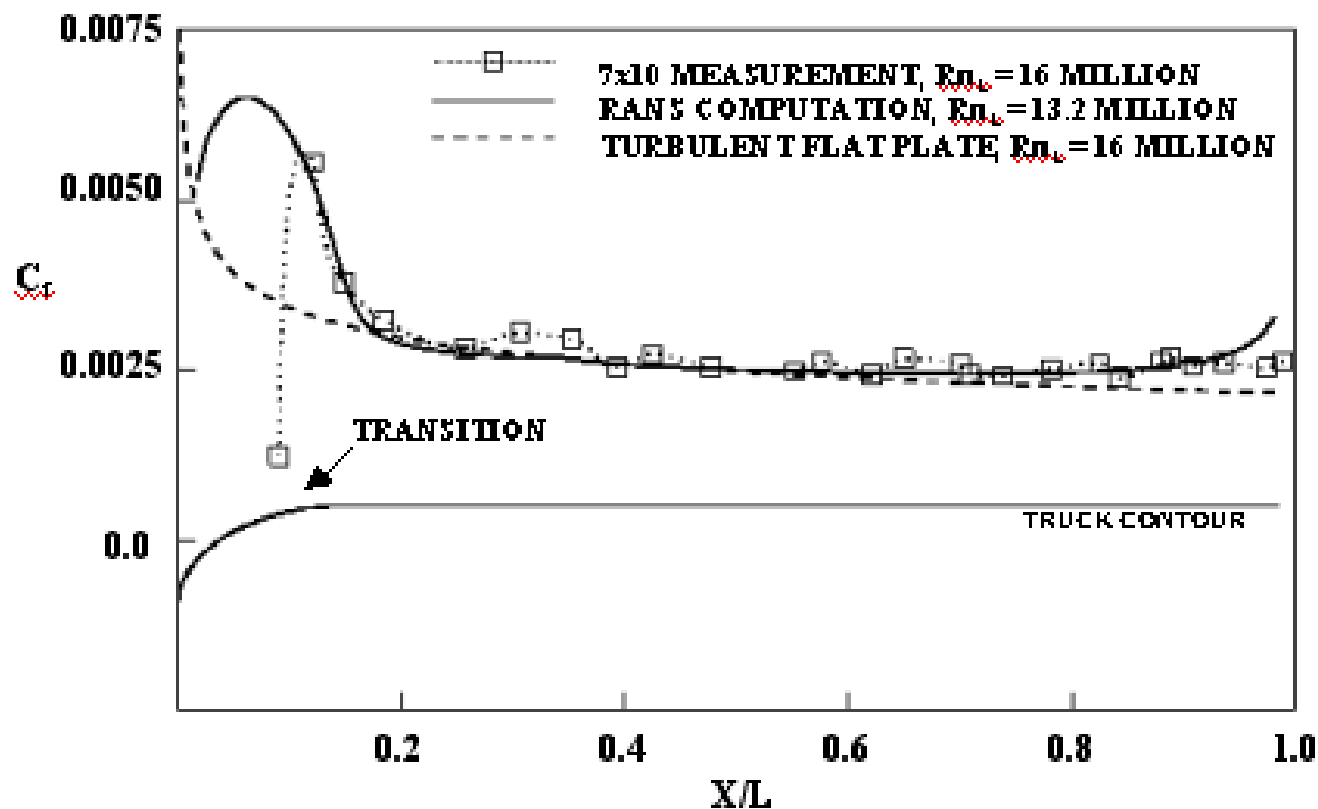




# Skin Friction Comparison NASA Experiment

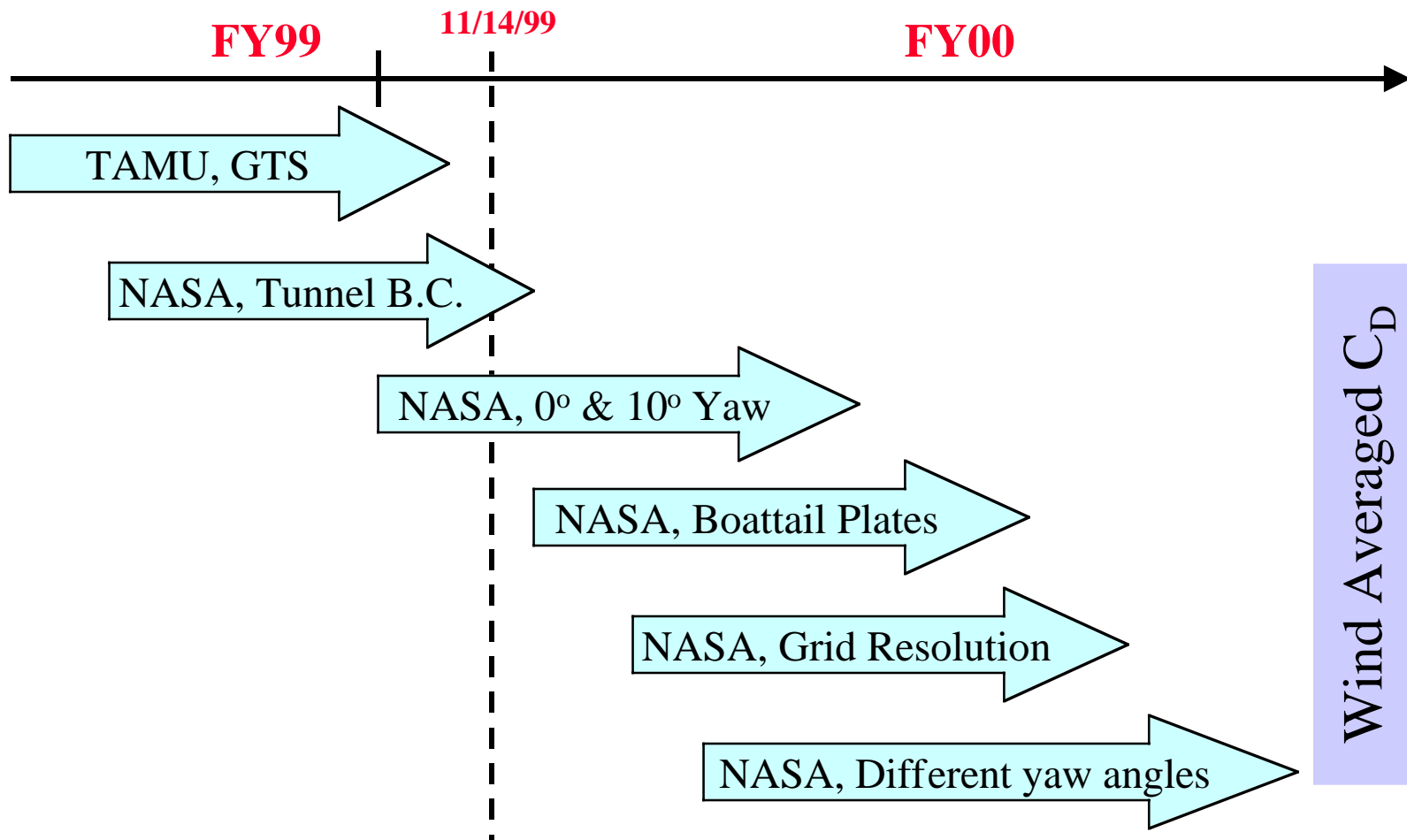
Greg Zilliac, Dave Driver, NASA ARC

0° yaw, top surface, center line





# Ongoing Sandia Simulations





## Concluding Remarks

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- **Demonstrate application of modern, state-of-the-art CFD technology to predict flow field around heavy vehicles.**
- **Starting with simplified shapes (such as GTS) for validation and then increase complexity**
- **Total vehicle aerodynamics (e.g., absolute drag)**
- **Relative effects from design changes (e.g., boattail plates, gaps, mirrors, etc.)**

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# A Computational Study of the Influence of Boattail Plates on the Trailer Flowfield

**Dan Flowers, Jerry Owens, Rose McCallen, Tim Dunn**

**Lawrence Livermore National Laboratory  
Livermore, CA**

**November 14, 1999**



## Several approaches are being used to simulate the GTS

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### SNL

Reynolds Average Navier-Stokes (RANS)/ **Detached Eddy Simulation (DES)**  
Compressible Finite Volume Code  
Average “Steady” Solution/**Unsteady Solution**  
Widely used - may not predict drag correctly

### LLNL

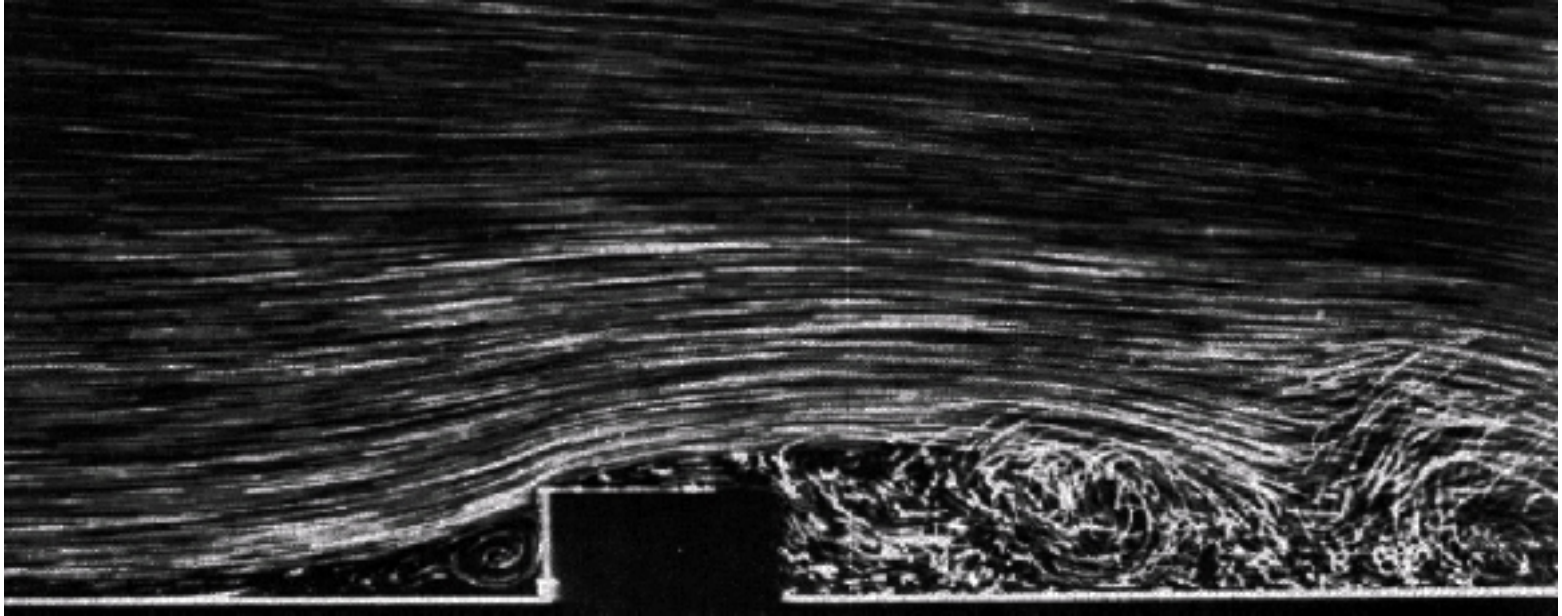
Large Eddy Simulation (LES)  
Compressible Finite Element Code  
Unsteady Solution of large scales/approximation of the small scales  
Computationally intensive

### Caltech

Direct Numerical Simulation/ **LES**  
Vortex Method  
Gridless  
In development

## Turbulent flow contains eddies ranging from large-scale to small-scale

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**Large-eddy simulation captures the large-scale motion and approximates the small-scale motion.**

all turbulent motions = large-scale motions + small-scale motions

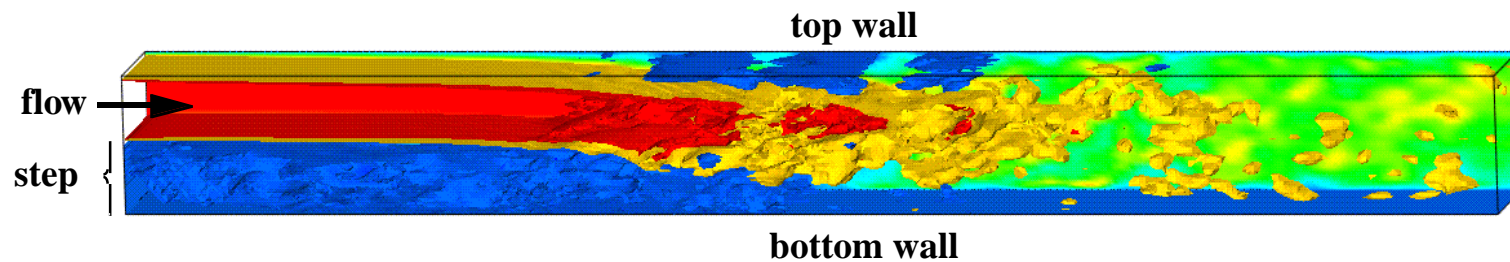
= 'resolved' scale + 'subgrid' scale

$$u_{\alpha} = \bar{u}_{\alpha} + u'_{\alpha}$$

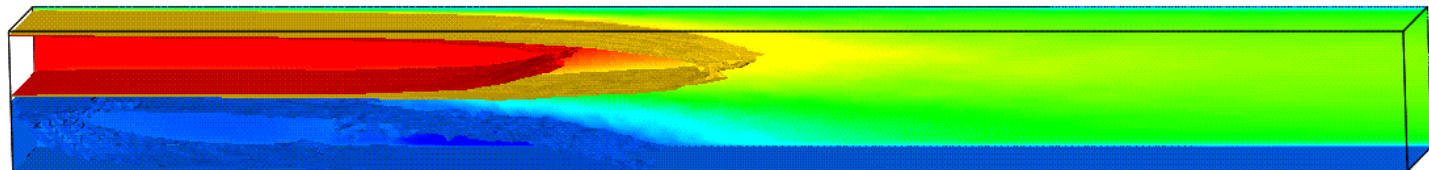


## Streamwise Velocity

**LES: instantaneous and/or time-averaged with 1 empirical parameter**



**RANS: only time-averaged with many empirical parameters**



## We are focusing on two areas

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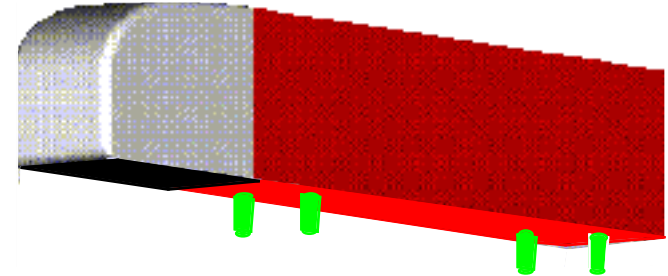


### **Simulating full GTS geometry**

**NASA 7'x10' wind tunnel tests**

**Course mesh ~ 6 million elements**

**Results will be validated with experiments**



### **Effect of boattail plates on aerodynamic drag reduction**

**Modeling only back end to conserve elements**

**Geometry based on GTS model**

**Investigating fundamental flow phenomenon**

## **Boattail plates have been shown to reduce drag**

---



**Full-scale truck in wind tunnel**



**Model in wind tunnel**

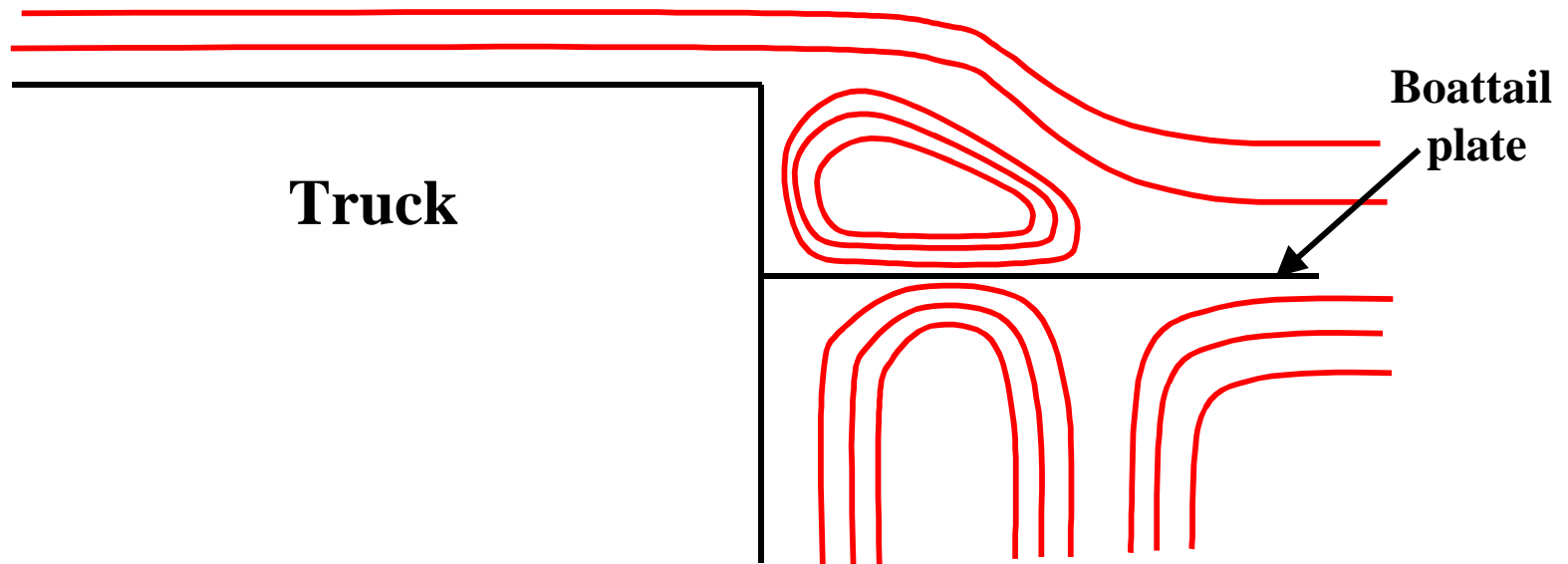


**Plates developed by Continuum Dynamics, Inc.**

## A recirculation zone forms in the boattail plate offset



This recirculation zone draws the wake in behind the body

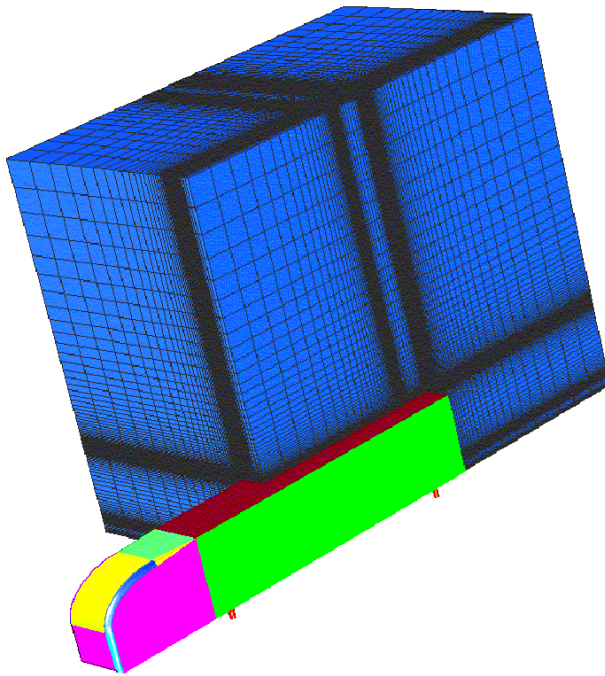


# Solving the 3D turbulent flow field requires extensive computational resources

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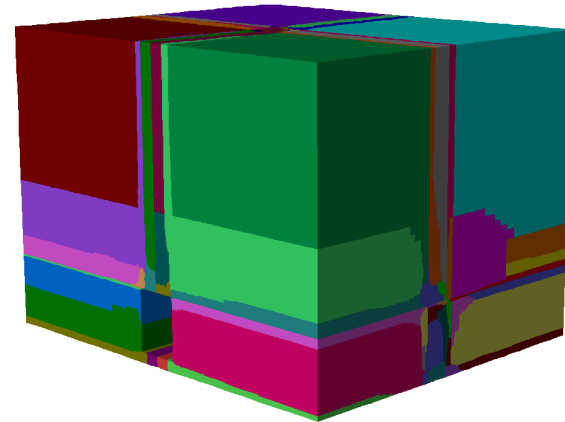
**Compressible flow simulation**



**Half of 3 million  
element grid**

**148 computational domains**

**148 processors on ASCI Blue  
massively parallel machine  
(IBM)**

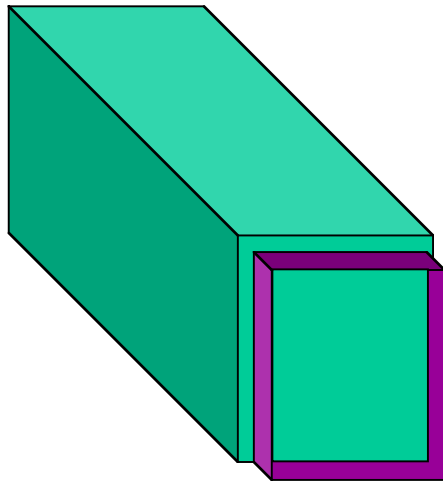
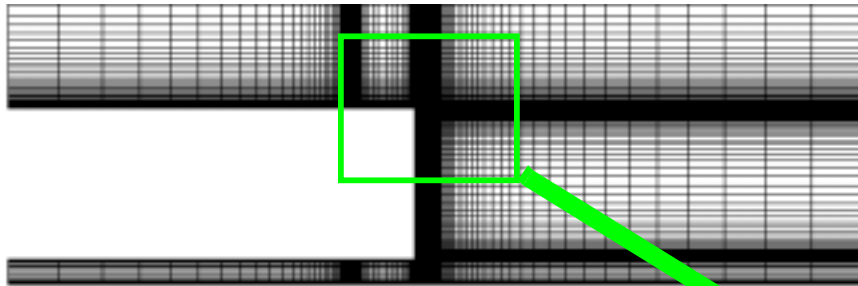


**Domain decomposition**

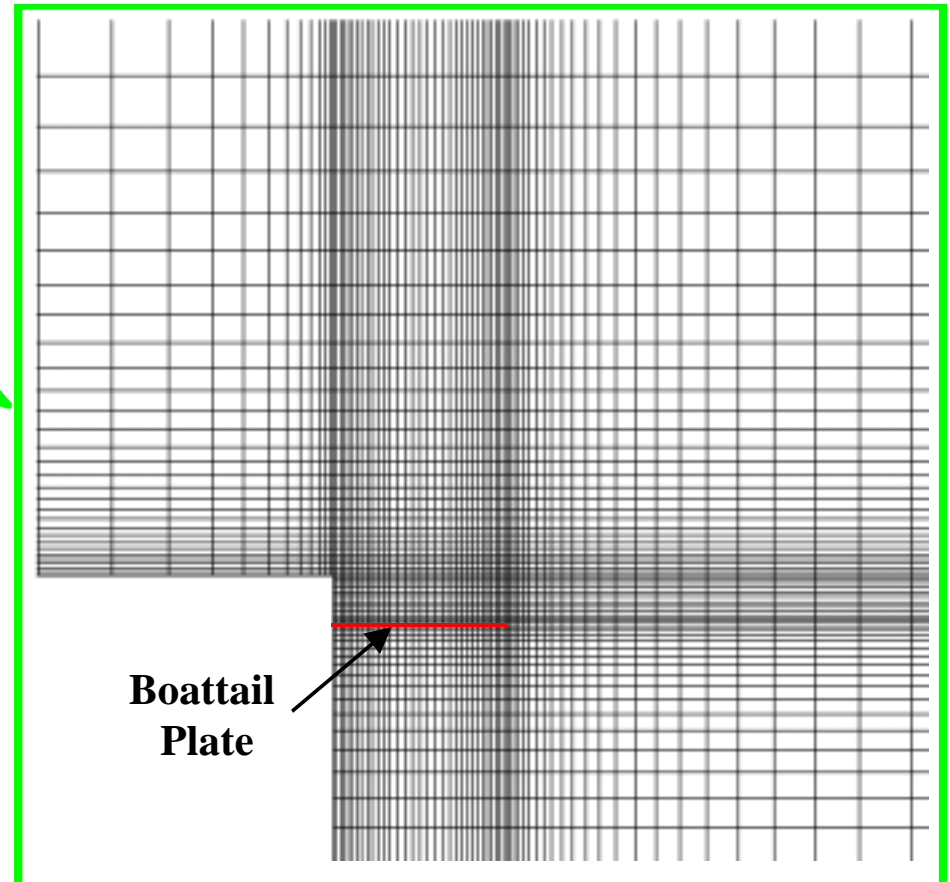
**The problem size is approximately 3 million elements  
with 1 mm wall resolution**



**Grid on rear of trailer**



**Refinement at walls and plates**



**Resolution of the wall determines the time step**

# Computations predict the reduced wake size as seen in experiments

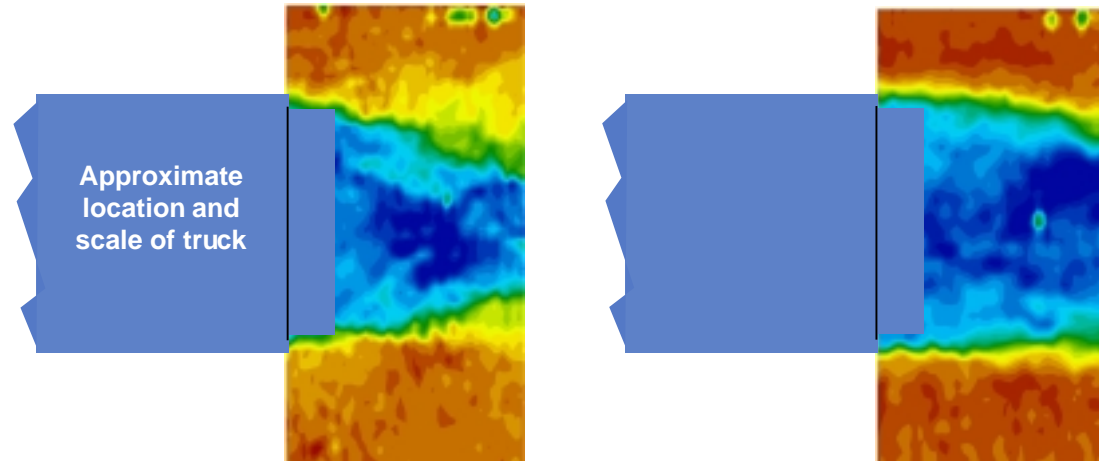


## Top View: Streamwise velocity component

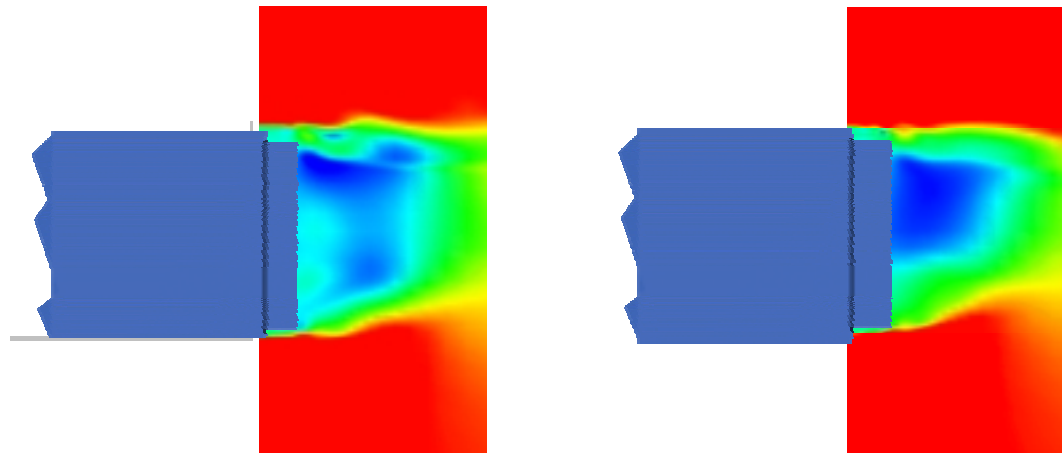
Without plates

With plates

Experiment



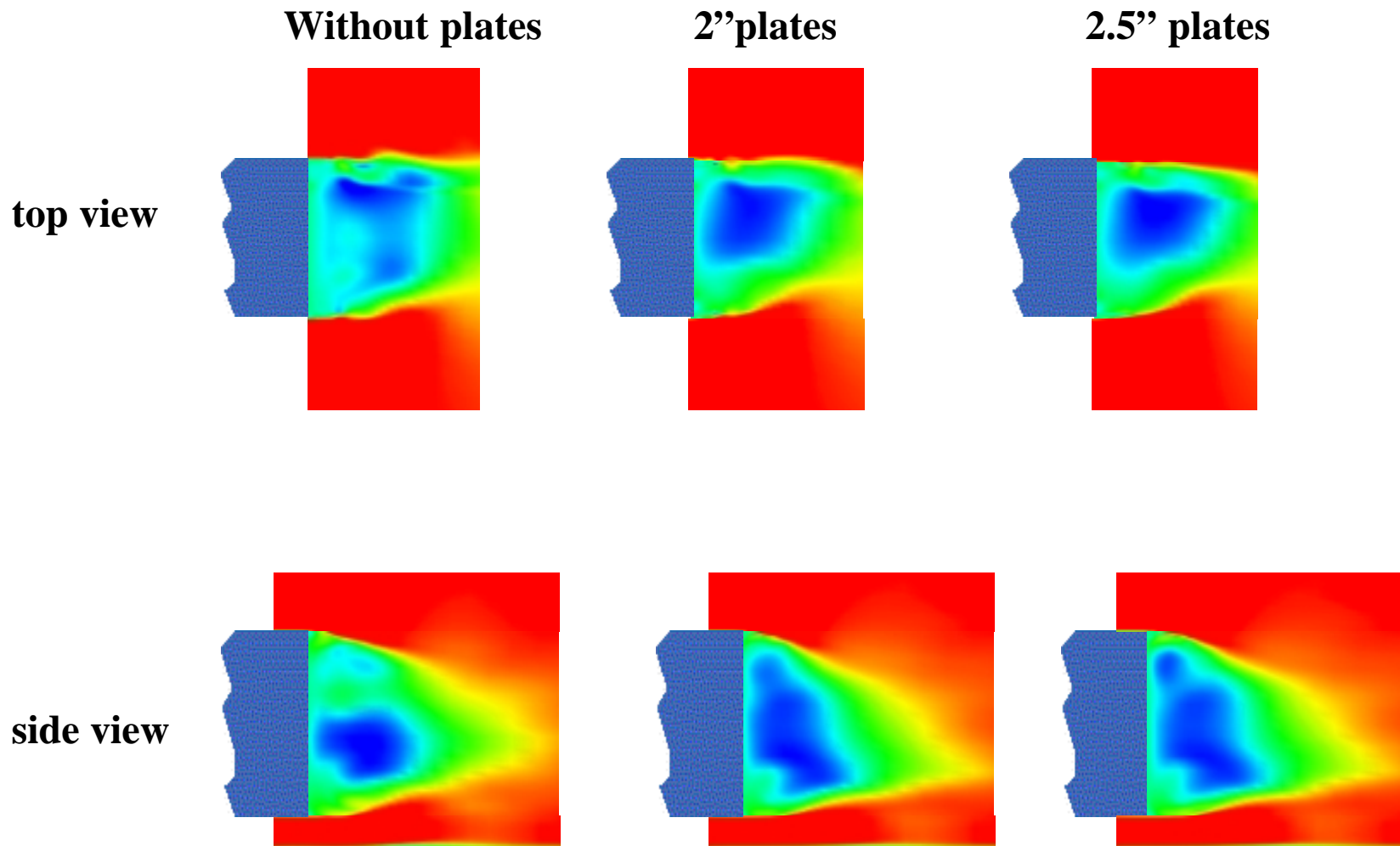
Computations



# Effect of boattail plate length is being studied



## Streamwise Velocity Component



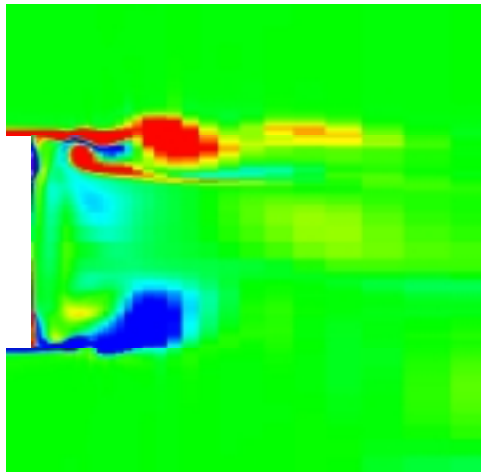
# Out of plane vorticity in trailer wake

---

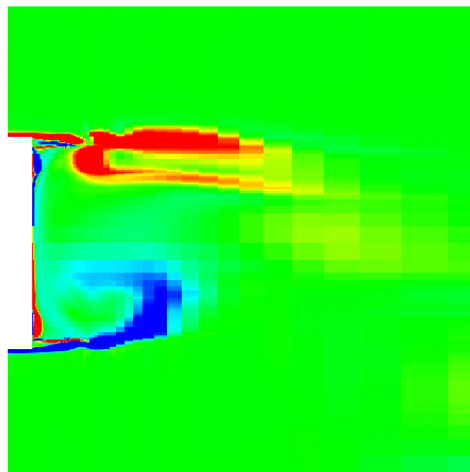


## Top View

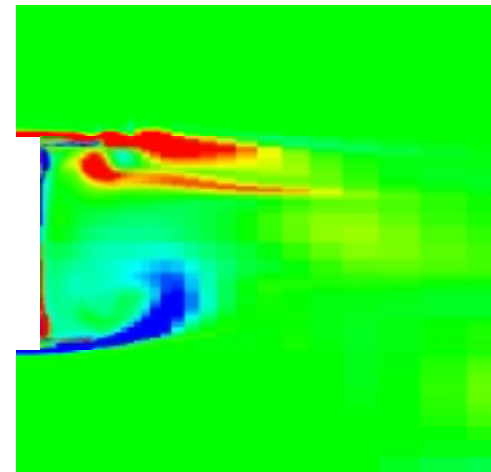
Without plates



2" plates



2.5" plates



## Summary

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**Boattail plates have been shown experimentally to reduce drag**

**FEM/LES is being used to understand the flow phenomena and the effect of plate length**

**Preliminary results indicate similar trends as the experiments**

**Validation of simulations with experiments is ongoing**

# Simulation of Complex, Unsteady Flows Using a Grid-Free Vortex Method

A. Leonard

Graduate Aeronautical Laboratories  
California Institute of Technology

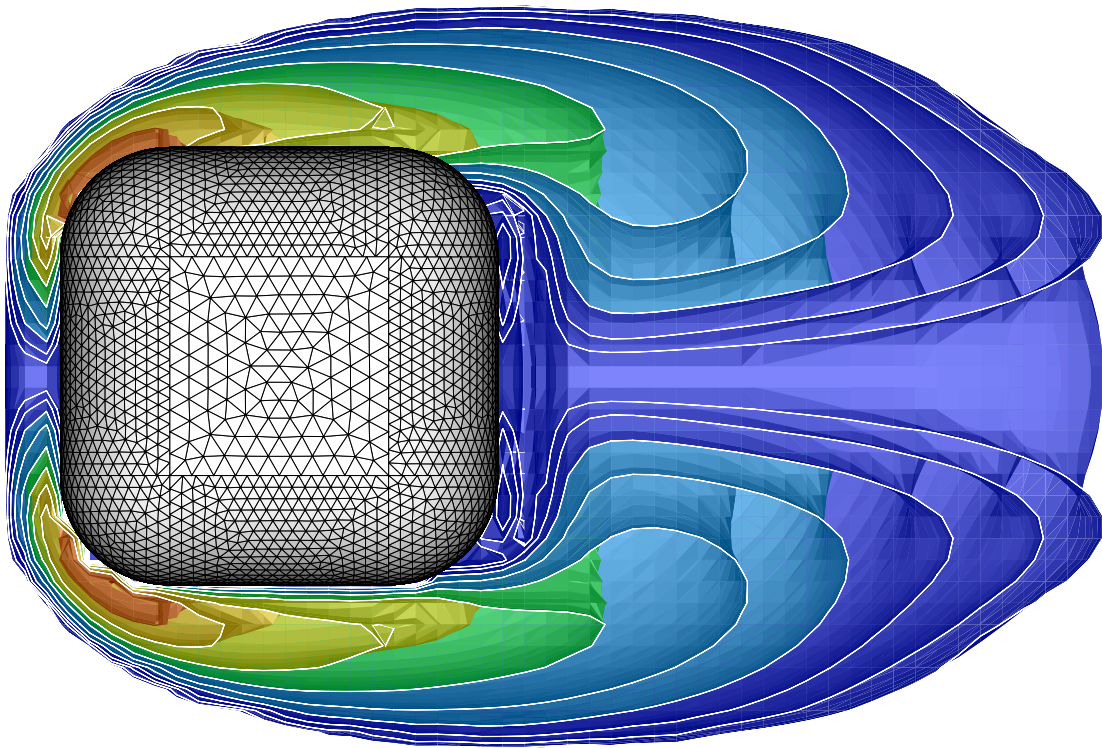


M. Brady, L. Barba, M. Rubel

## Essentials

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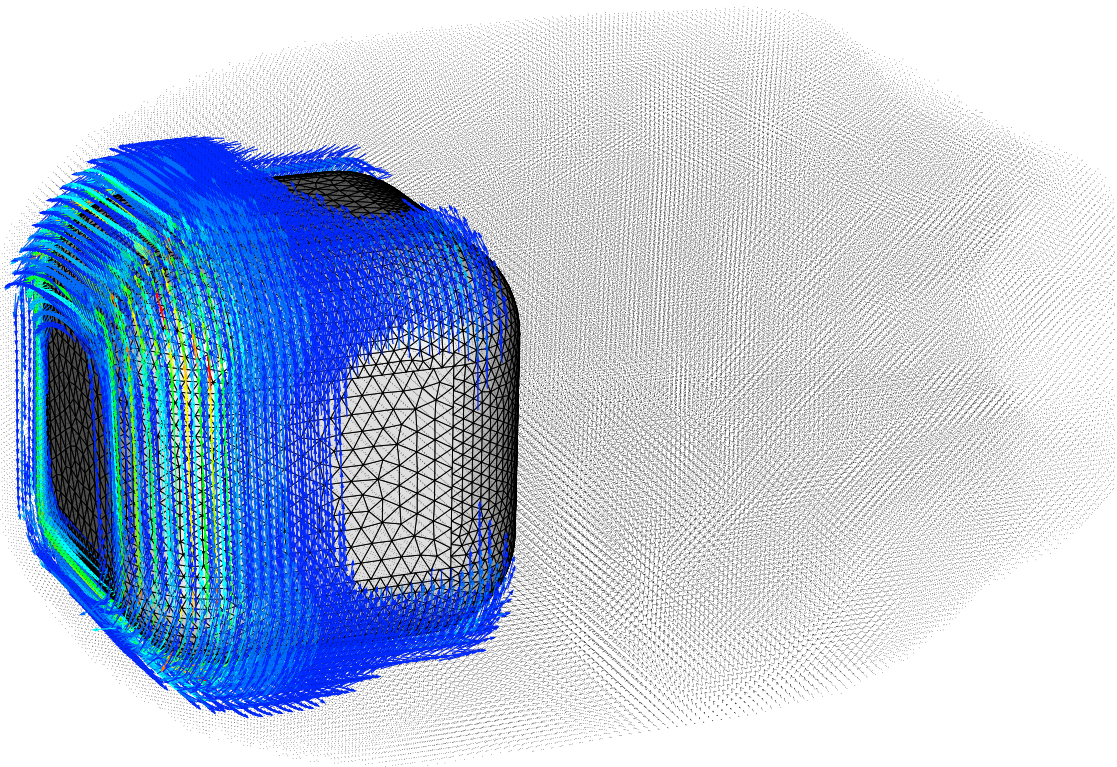
- Numerical technique to solve the Navier-Stokes Equations
- Suitable for Direct Simulation and Large-Eddy Simulation
- Uses vorticity (curl of the velocity) as a variable
- Computational elements move with the fluid velocity



## Advantages

---

- Computational elements only where vorticity is non-zero
- No grid in the flow field
- Only 2D grid on vehicle surface
- Boundary conditions in the far field automatically satisfied



# Vortex Method as a Flow Model

## Previous limitations (1960s and 70s)

---

- Inviscid model – dynamics of the boundary layer ignored
- Computationally limited –  $O(N^2)$  operations per time step
- $N$  = only a few hundred to a few thousand computational elements feasible
- Dynamics of the wake and force coefficients dependent on adjustable parameters

## Recent Developments (90s)

---

- Viscous effects treated accurately
- Fast Vortex Algorithm –  $O(N \log N)$  operations per step
- $N$  = one to 100 million computational elements feasible
- Dense system of computational elements solves fluid equations
  - Direct simulation for low Reynolds number
  - Large-Eddy simulation for high Reynolds number
- Large-scale, load-balanced parallel computing

# Treatment of Surface Vorticity

## Standard Panel Method for N Panels

---

- Computationally and storage limited –  $O(N^2)$  matrix elements computed and stored with  $O(N^2)$  operations per time step
- Only  $N = 10,000$  to  $20,000$  feasible

## Advanced Panel Method

---

- Extendible to high order accuracy
- Computationally efficient –  $O(N)$  storage locations with  $O(N \log N)$  operations per time step
- $N = 10^6$  no problem
- Triangular mesh with automatic refinement

# Large-Eddy Simulation

## Direct Simulation not Sufficient (1990s)

---

- Direct Simulation possible for Reynolds no.= $10^3$  to  $10^4$   
(at parking speeds – 0.01 mph)
- $N = 10^{12}$  elements (approx. 20 Terabytes) required for  
Reynolds no.= $5 \times 10^6$   
(at highway speeds)

## Large-Eddy Simulation Required

---

- Treatment of small-scale (subgrid-scale) turbulence in the wake
- Treatment of small-scale turbulence in the boundary layers
- Treatment of fluidic actuators, blowing/suction, vortex generators and other flow control devices

# Rounded Cube DNS

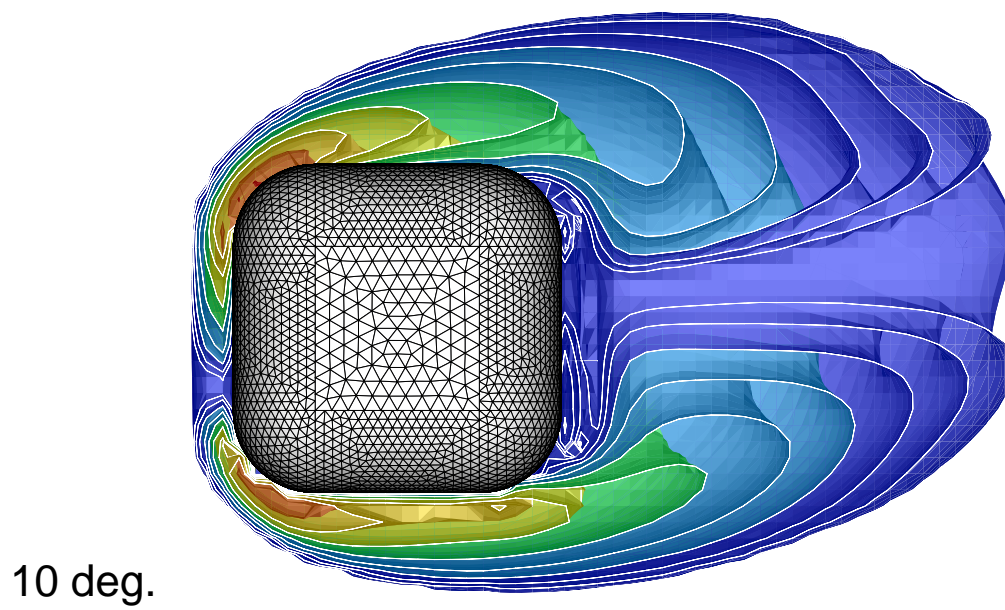
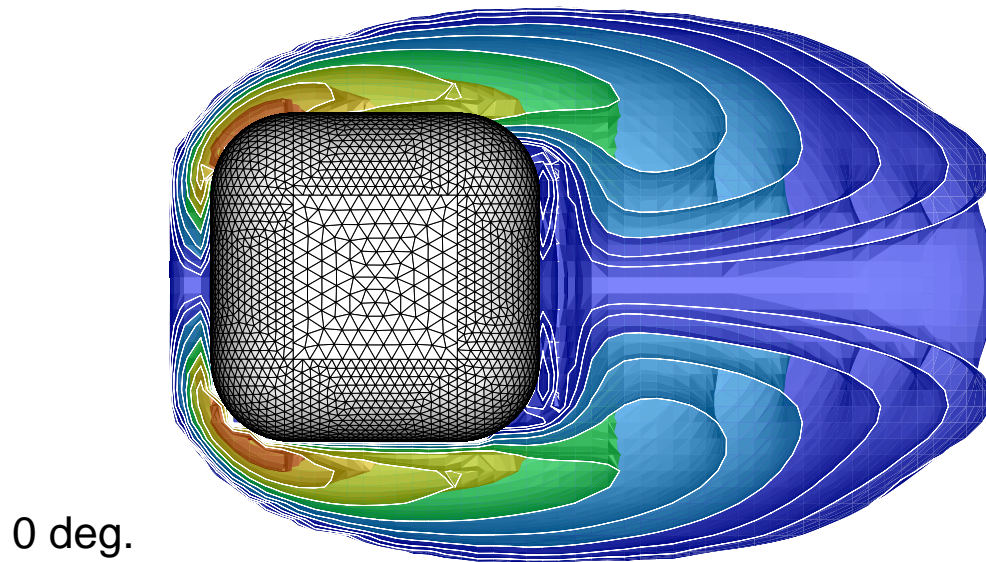
## Features

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- Adjustable leading edge curvature
- 0, 10 deg. yaw
- Reynolds no. 100
- Body forces

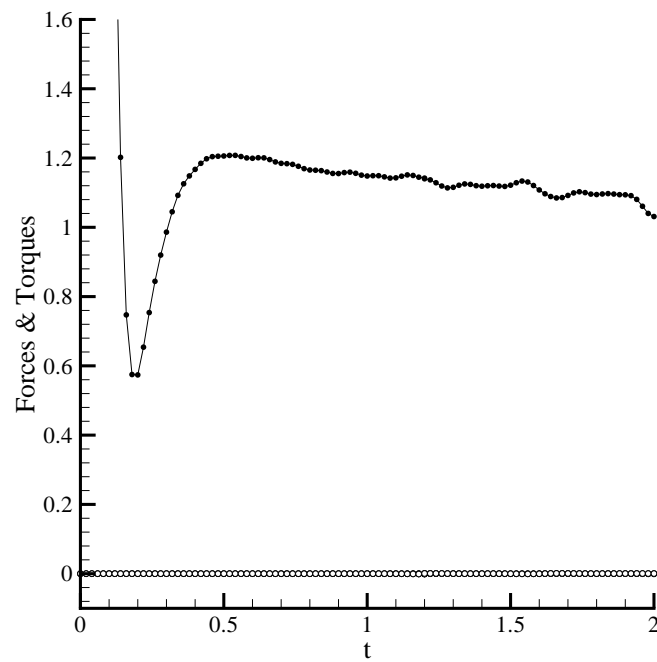
## Vorticity Contours

---

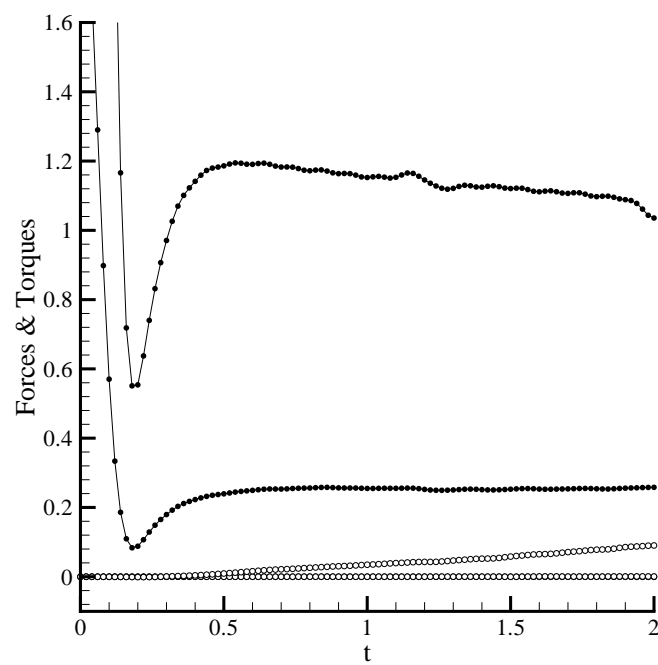


# Body Forces

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0 deg.



10 deg.

## Status / Future Work

- Incorporation of GTS model into full Vortex Method
- Implementation of the Vortex Method for arbitrary complex geometries
- Analysis of Reynolds number effects (leading edge curvature)
- Subgrid stress model for Large-Eddy Simulation

# ***PNEUMATIC AERODYNAMIC DEVICES TO IMPROVE THE PERFORMANCE, EFFICIENCY, ECONOMICS AND SAFETY OF HEAVY VEHICLES***

**DOE Third Workshop on Heavy Vehicle Aerodynamics**

**by**

**Robert J. Englar**

**Principal Research Engineer**

**Georgia Tech Research Institute**

**Aerospace, Transportation & Advanced Systems Laboratory**

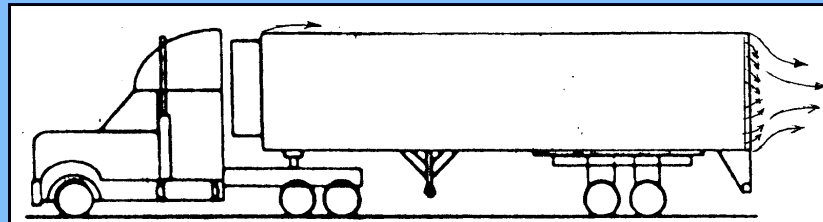
**Atlanta GA**



Pneumatic Aerodynamics



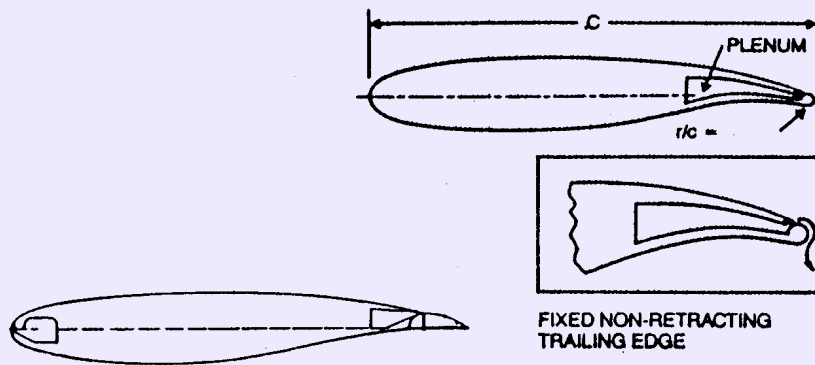
GTRI FutureCar Pneumatics



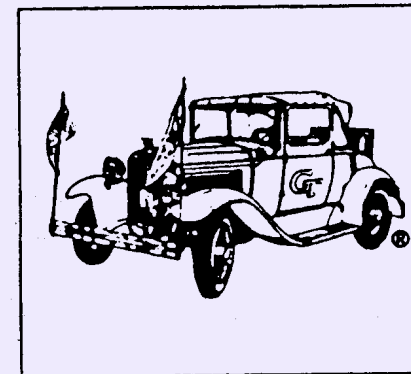
**Advanced  
Heavy Vehicles**

# OUTLINE OF PRESENTATION

- **Introduction: Potential of Aerodynamic Improvements For Commercial Vehicles**
- **Pneumatic Aerodynamics**
- **Lessons from Application of Pneumatic Aerodynamics to Automobiles, FutureCar**
- **Current DOE Program: "Pneumatic Aerodynamics for Heavy Vehicles"**
- **Pneumatic Aerodynamics Applied to Large Commercial Vehicles**
- **Conclusions and Recommendations**

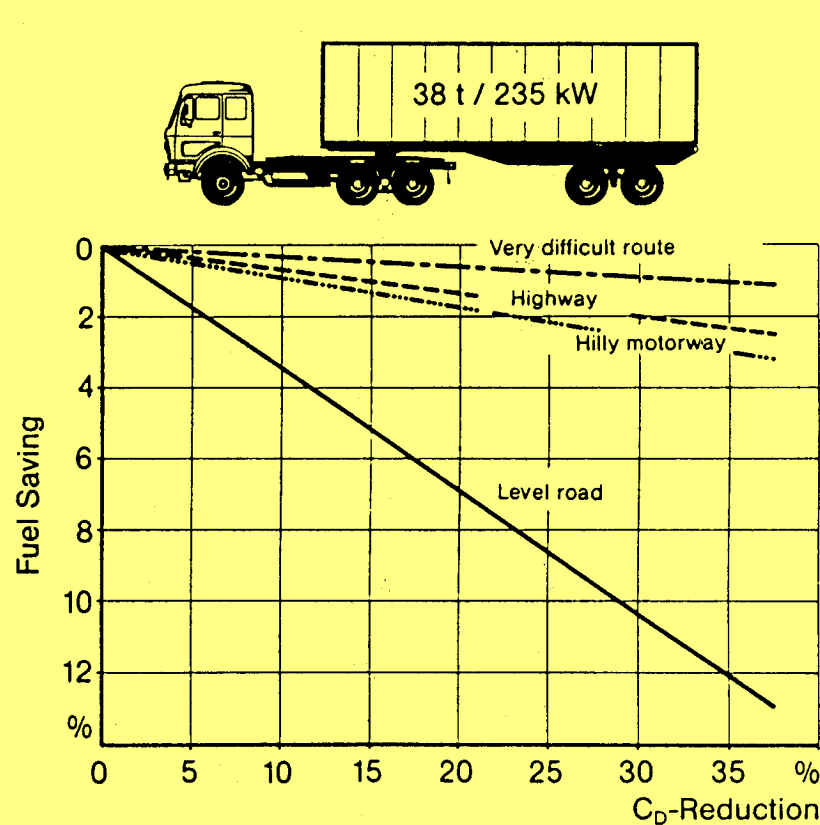


Advanced Pneumatic Aerodynamics

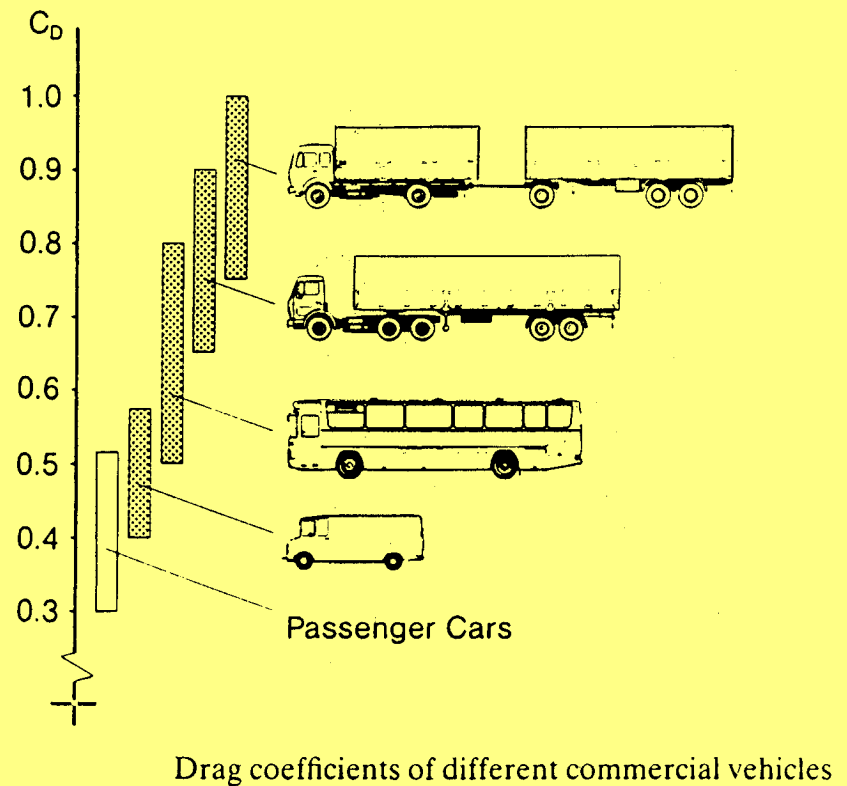


GT Automotive Experience

# HEAVY VEHICLE EFFICIENCY INCREASE FROM IMPROVED AERODYNAMICS: DRAG REDUCTION



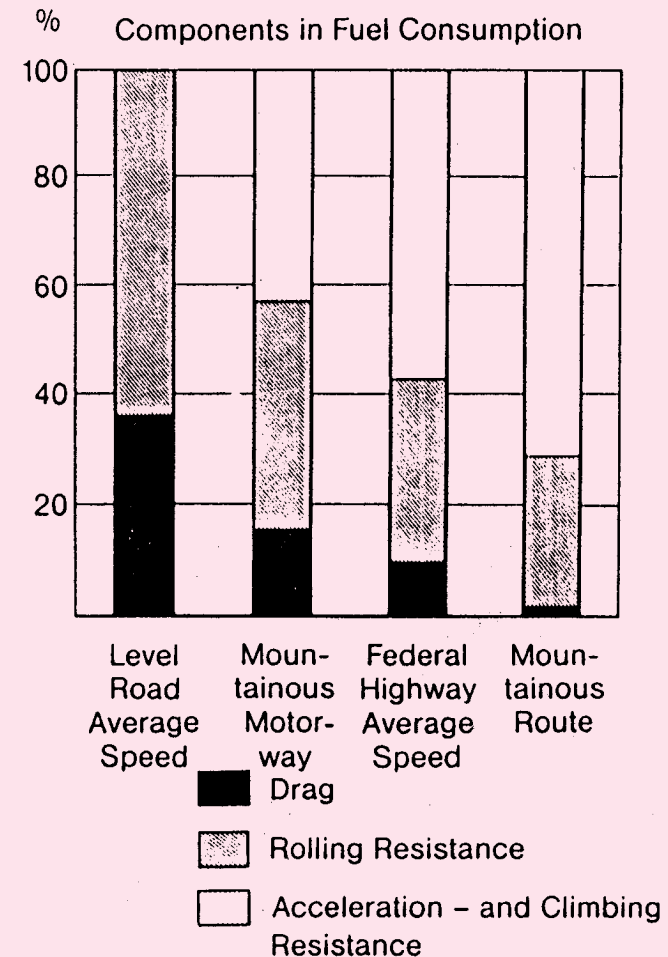
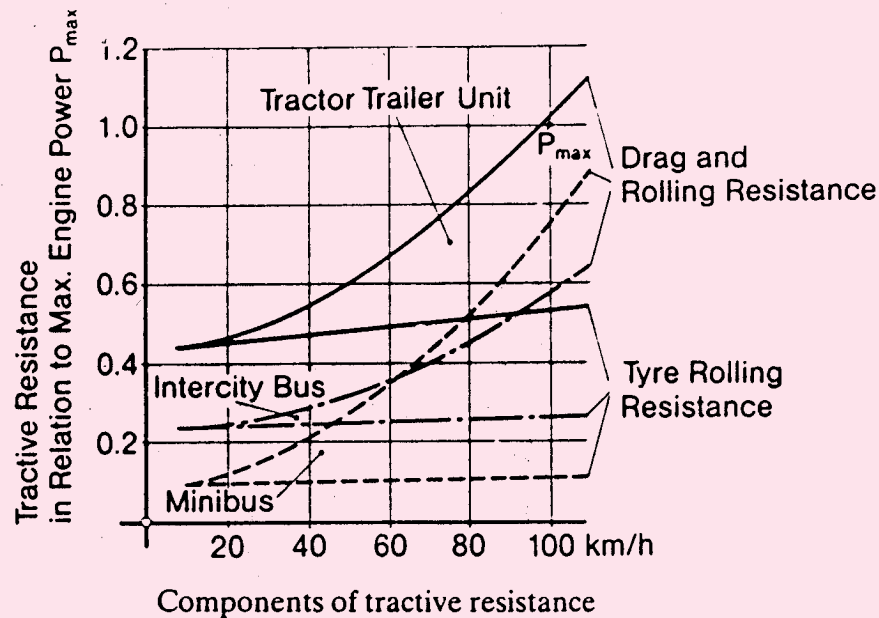
Influence of drag on fuel consumption of a 38-tonne semitrailer



Drag coefficients of different commercial vehicles

from Hucho, "Aerodynamics of Road Vehicles," 1990

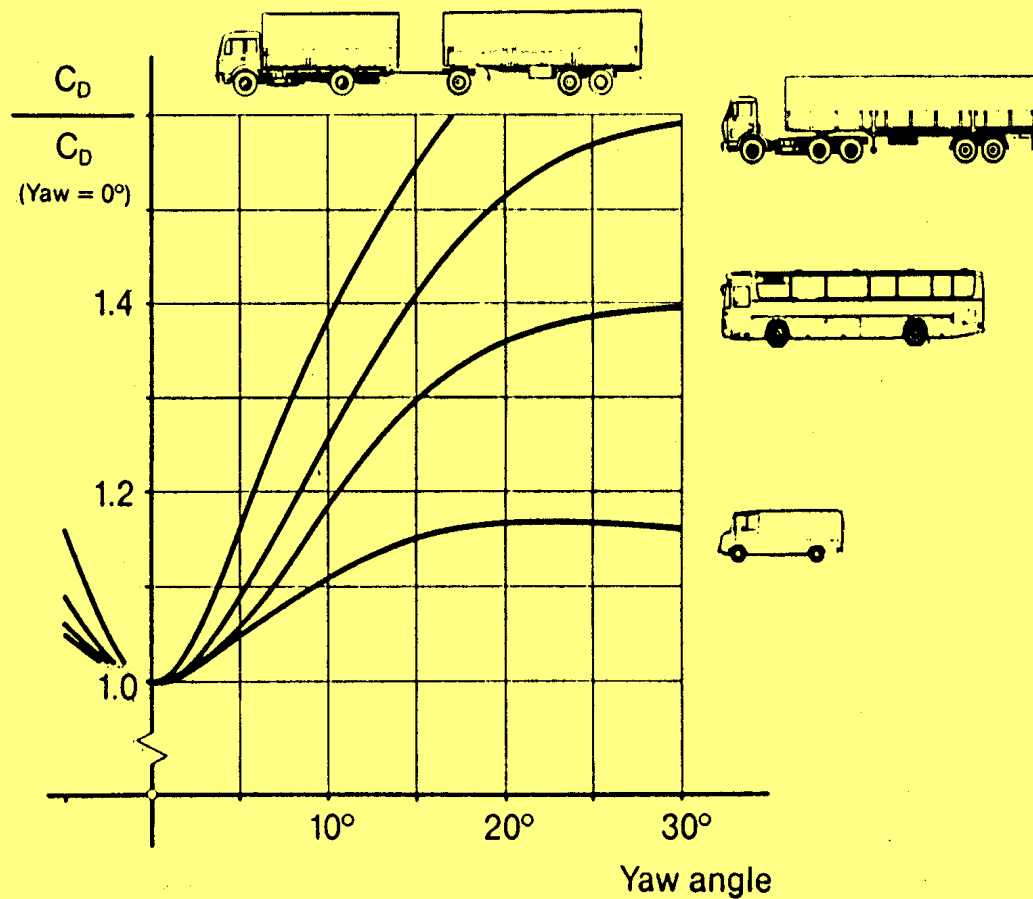
# EFFICIENCY INCREASE FROM IMPROVED AERODYNAMICS: COMPONENTS OF TRACTIVE RESISTANCE



from Hucho, "Aerodynamics of Road Vehicles", 1990

Fuel consumption of a 38-tonne tractor-semitrailer to overcome tractive resistance

# VEHICLE DIRECTIONAL SENSITIVITY TO THE WIND

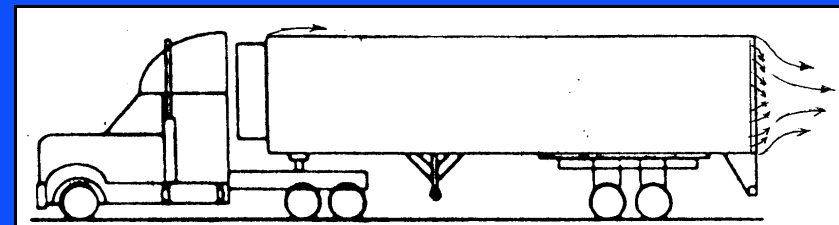
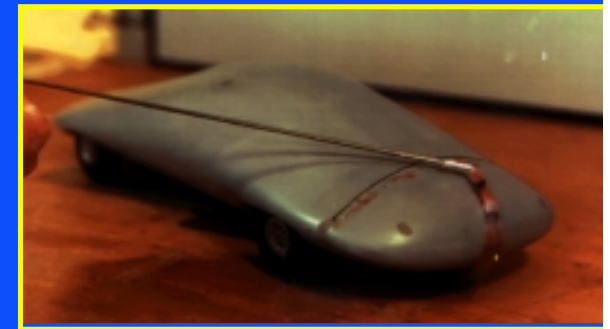
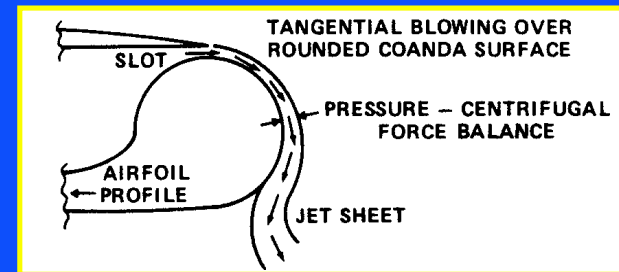


Drag versus yaw of different vehicle types

from Hucho, "Aerodynamics of Road Vehicles," 1990

# Circulation Control Technology

- ❁ Circulation Control is an innovative flow control technology that can dramatically improve aerodynamic/aeropropulsive performance and simplify mechanical complexity through pneumatic means.
- ❁ Circulation Control technology has previously been developed and flight-demonstrated for military/NASA aircraft (A-6/CCW, H2/CCR, CCW/USB, NOTAR).
- ❁ Leveraging GTRI “Future Car” IRAD investments, GTRI AERO is successfully transitioning this technology for NASA and non-DOD, non-military markets.
- ❁ New DOE award for “Pneumatic Aerodynamic Devices for Heavy Vehicles” is first part of a multi-phase concept-demonstration program.



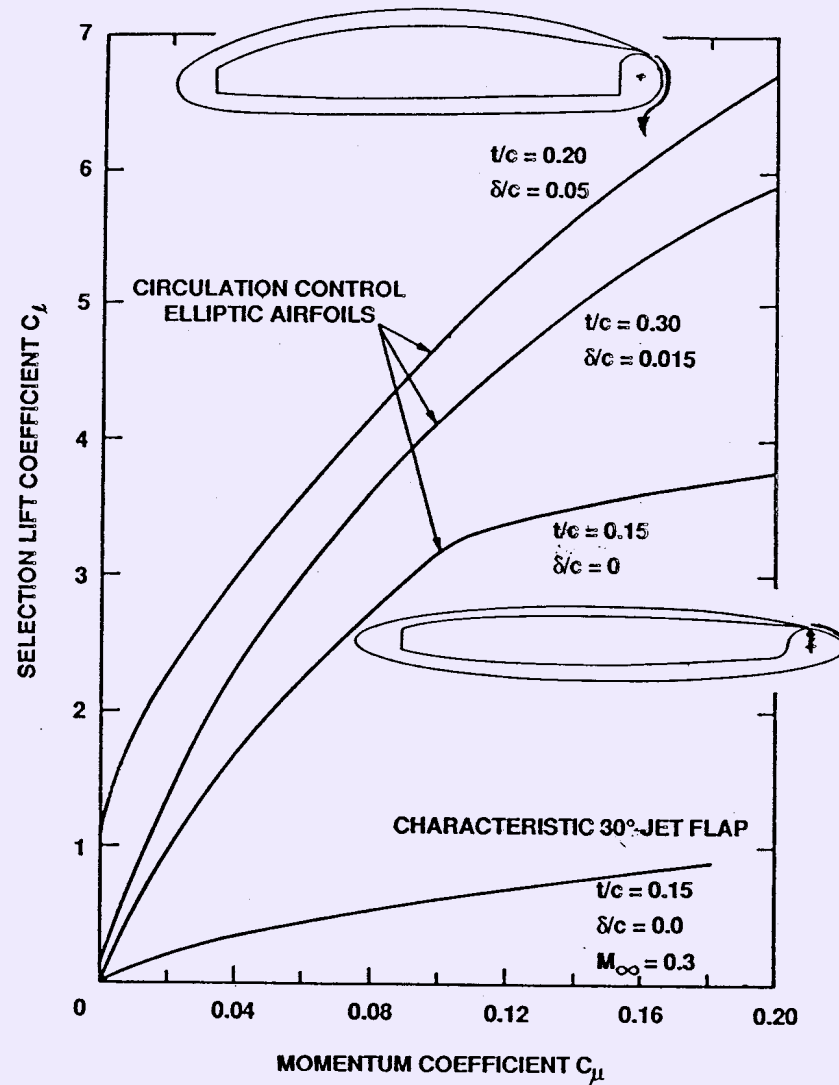
## BACKGROUND OF CIRCULATION CONTROL AERODYNAMICS EXPERTISE, NOW RESIDING AT GTRI

1967-1968: "Imported" from England, (C.C. Stowed Rotor at NGTE) by U.S. Navy, <b>David Taylor Naval Ship R&amp;D Center</b>	Aerodynamics Lab., <b>DTNSRDC</b>
1968-1972: Development of C.C. Airfoils for Rotary Wing (CCR, X-Wing)*	DTNSRDC
1973-1975: C.C. Wing High-Lift Airfoil Development*	DTNSRDC
1975-1979: A-6/CCWing STOL Demonstrator Flight Test	DTNSRDC
1979-1984: Advanced CCW and CCW/Powered Lift Programs*	DTNSRDC
1984-1989: Advanced CCW, Powered Lift & Pneumatic Concepts*	Advanced Flight Sciences Dept. <b>Lockheed-Georgia Co</b>
1989-1999: Advanced Aerodynamic Concept Development*	Aerospace Sciences Lab <b>Georgia Tech Research Institute</b>
1990-1999: In-Ground-Effect Unlimited Hydroplane & Race Car Development *	Aerospace Sciences Lab, GTRI
1994-1999: Pneumatic Automobile Research & DOE Programs*	Aero Sciences Lab, GTRI
1993-1999: CCW for Advanced Transports (NASA) & High Speed Aircraft (AF) *	Aero & Transportation Lab, GTRI

\* Miscellaneous advanced pneumatic concepts and applications in other categories were developed in this time period. A large number of invention disclosures produced more than 15 patents.

- **GTRI's Robert J. Englar** led or was heavily involved in every one of these developments.

## Typical Blown-Lift-Generation Capabilities of Two-Dimensional Circulation Control Elliptic Airfoils at $\alpha = 0^\circ$



Momentum Coefficient,  
 $C_{\mu} = m V_j / (q c)$

## A-6 / CIRCULATION CONTROL WING STOL DEMONSTRATOR AIRCRAFT & FLIGHT TEST RESULTS



**FLIGHT TEST RESULTS:** 140% Increase in Usable CL

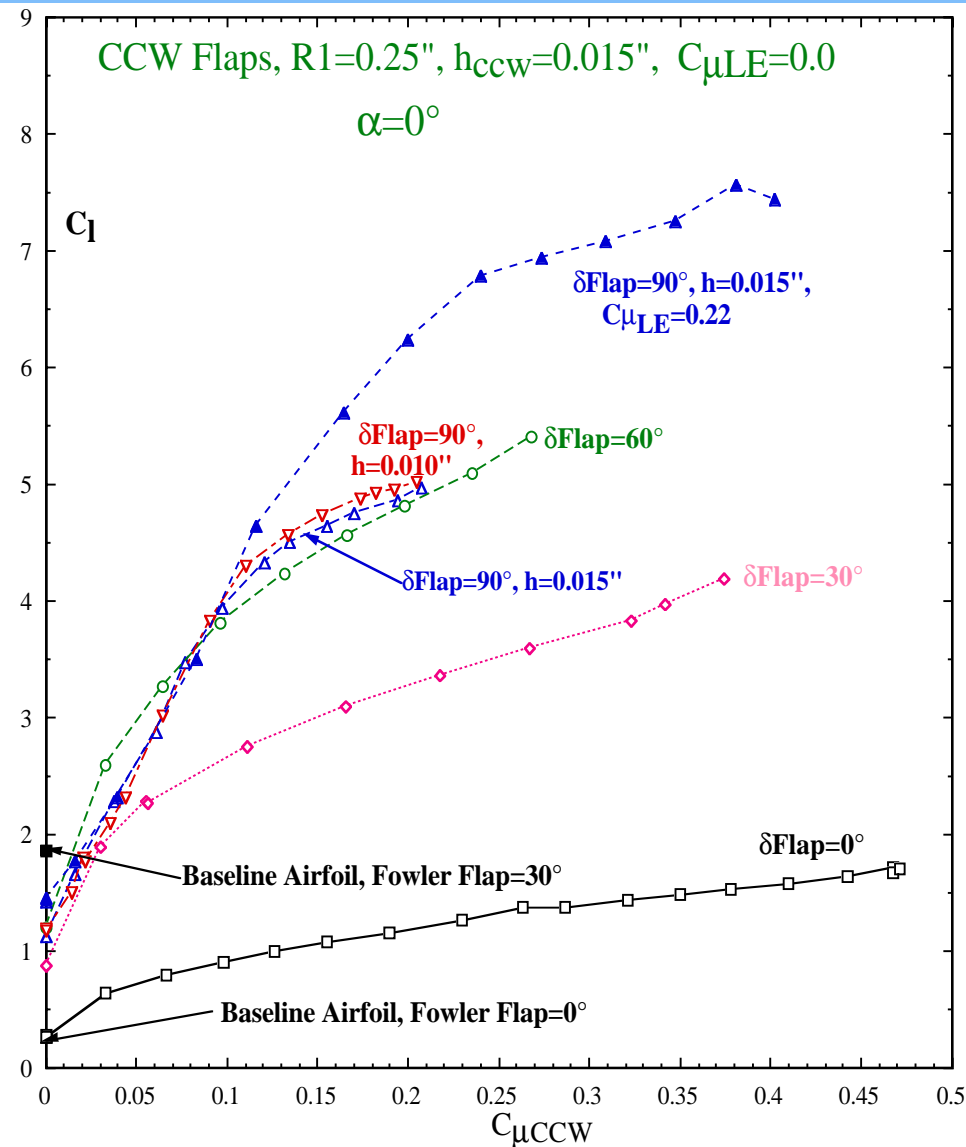
**CONFIRMATION OF  
FULL-SCALE CCW**

30-35% Reduction in Takeoff & Approach Speeds

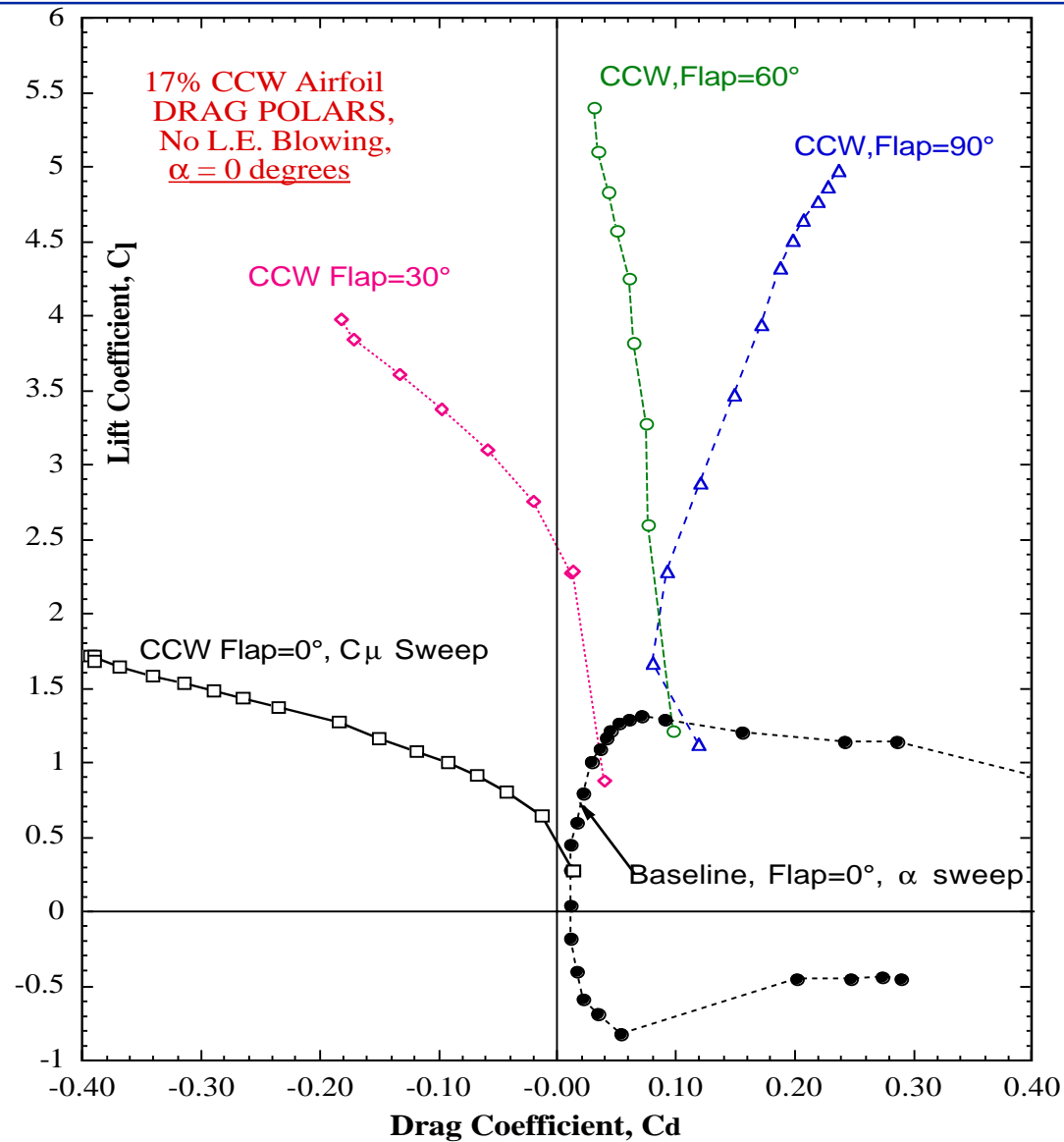
60-65% Reduction in Takeoff & Landing Ground Roll

75% Increase in Lifiable Takeoff Payload

## 2-Dimensional CCW AIRFOIL with DUAL-RADIUS FLAPS, LIFT VARIATION WITH BLOWING AT $\alpha=0^\circ$

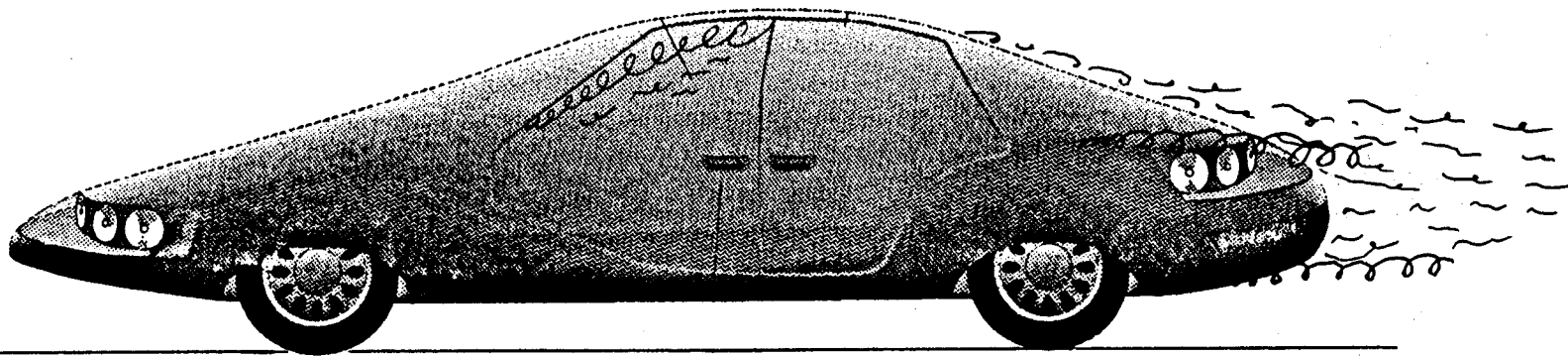


## 2-D CCW AIRFOIL with DUAL - RADIUS FLAPS, DRAG POLARS, THE PENALTY FOR LIFT ??



# **GTRI FutureCar Pneumatic Aerodynamics Project (Now Completed & Concepts Confirmed at GTRI)**

**GOAL: Apply Aerodynamic Blowing Techniques to a Streamlined Automobile Configuration to Improve its Aerodynamic and Stability Characteristics**



***2 Patents Issued to GTRI,  
1 Pending***

## **TYPICAL AERODYNAMIC PROBLEM AREAS FOR AUTOMOBILES:**

- DRAG CAUSED BY FLOW SEPARATION AND VORTEX FORMATION
- NOISE CAUSED BY FLOW SEPARATION AND VORTEX FORMATION
- DIRECTIONAL SENSITIVITY & INSTABILITY CAUSED BY YAW, SIDE FORCES & GUSTS
- POWER CONSUMPTION BY PROPOSED DRAG REDUCTION DEVICES & CONTROLS
- EXCESSIVE UPPER SURFACE LIFT--INCREASED DOWNLOAD REQUIRED

**UNIQUE SOLUTION: MULTI-PURPOSE APPLICATIONS OF  
PNEUMATIC (BLOWN) AERODYNAMIC TECHNOLOGY**

**Blown Model Installation in GTRI Tunnel on a 2-point Yaw Strut  
with Air Supply Line, and Showing Blown Ground Effect Simulation**

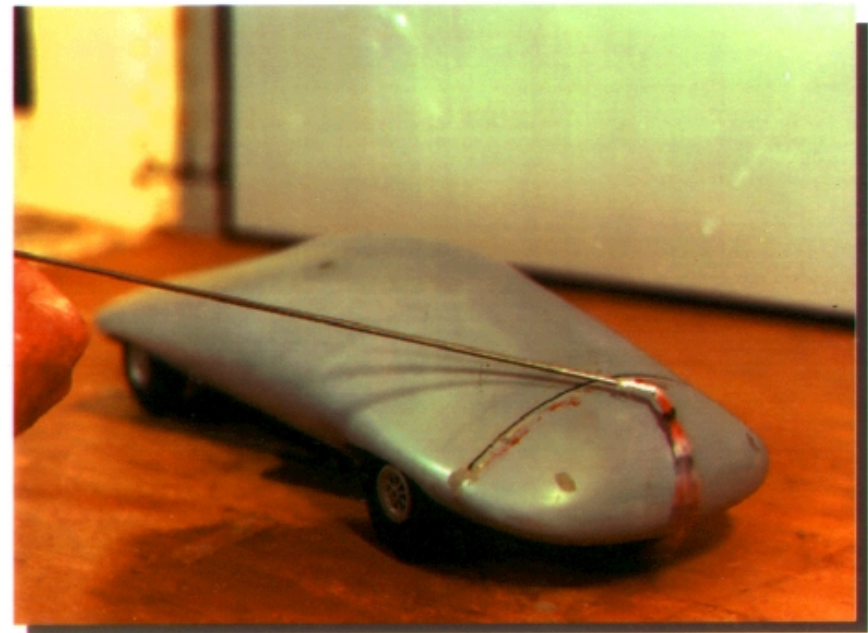


Tangential Floor Blowing Slot

## Experimental Confirmation of Pneumatic Aerodynamic Concepts on GTRI FutureCar Model, Showing Blowing Jet Turning



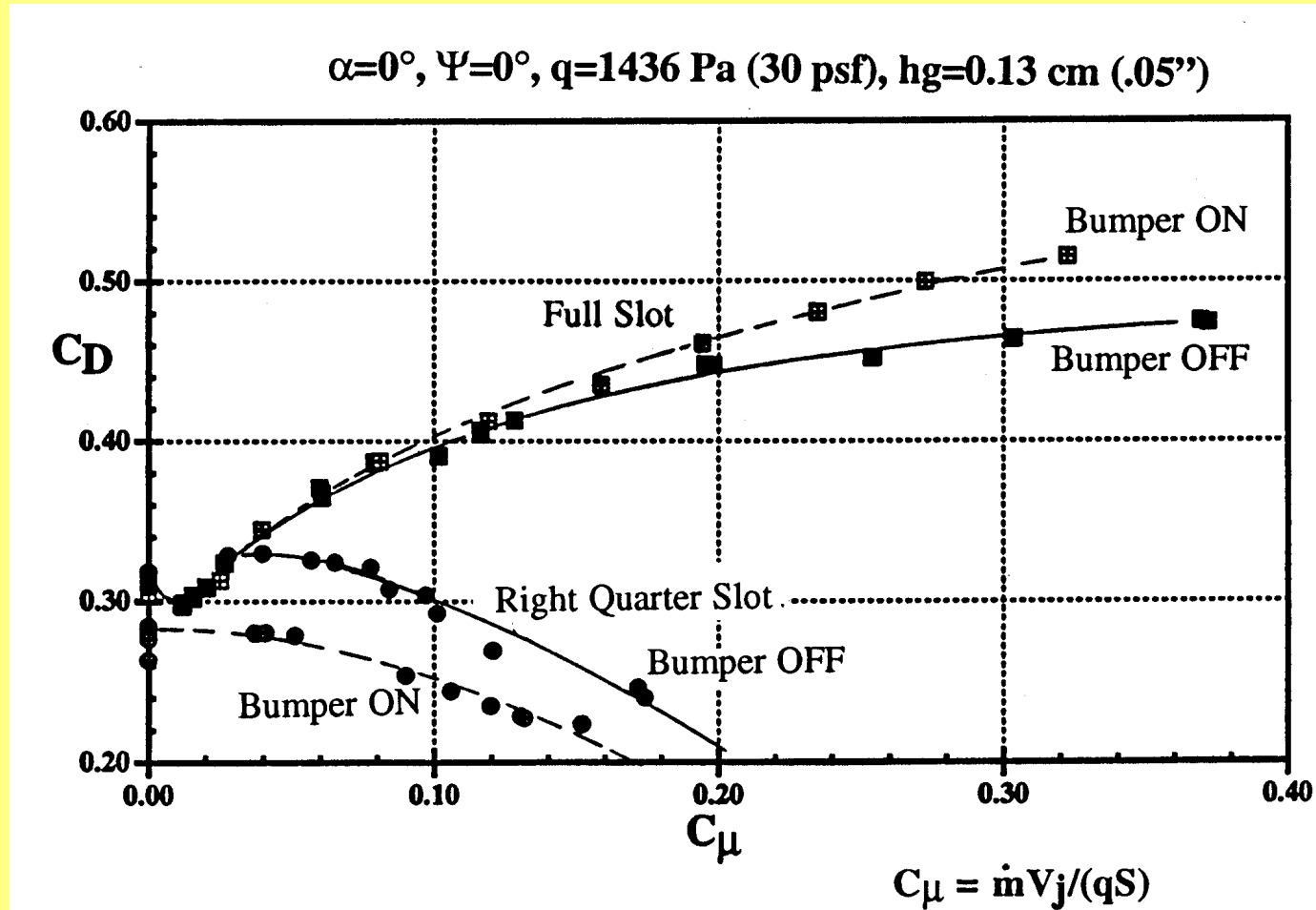
Blowing Slot Adjustment and Checkout  
in the GTRI Model Test Facility



Blowing Slot & Flow Turning Over Trunk  
of Streamlined Car Model

# Effect of Blowing on GTRI FutureCar Drag at Yaw Angle = 0° and Pitch Angle = 0°, Various Configurations

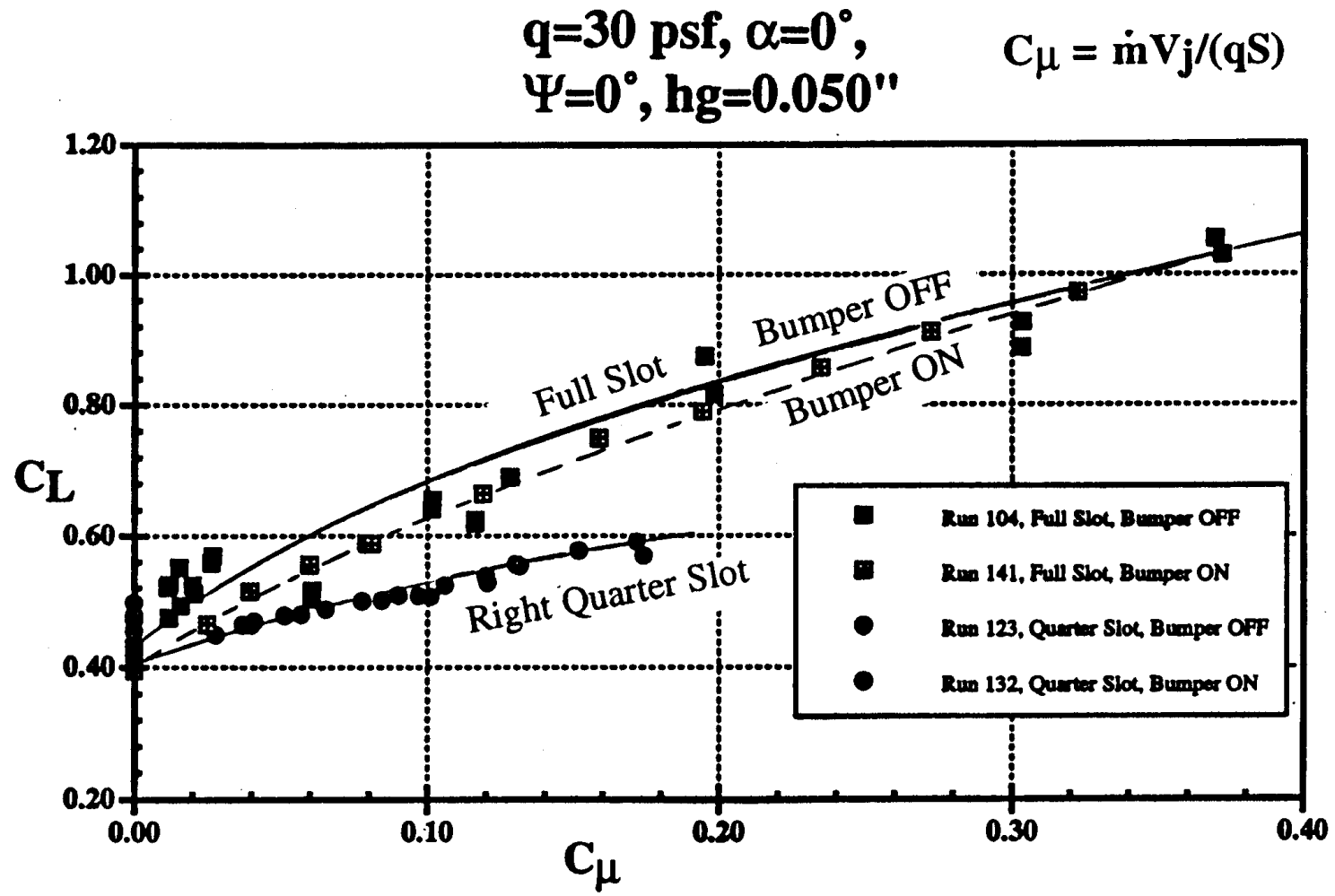
Drag Decreased(Cruise) or Increased (Braking), Depending on Configuration and Blowing



S=Frontal area

# Effect of Blowing on GTRI FutureCar Lift at Yaw Angle= 0° and Pitch Angle = 0°, Various Configurations

Lift Increased by Blowing; Download (-Lift) Increased by Blowing Lower Surface Slot



## Potential For Pneumatic Aerodynamics Applied To Heavy Vehicles, as Confirmed at GTRI Aerospace and Transportation Lab

### Experimentally Confirmed Blowing Benefits on GTRI FutureCar:

- Drag reduction of 35%; increase of 100%, depending on configuration
- Lift increase of more than 170%; similar download (-lift) increases
- Lateral/directional stability restored at large sidewind angles

### Potential Benefits of CC Pneumatics Applied to Heavy Vehicles:

- Pneumatic devices on back of vehicle, **blowing slots on all sides**
- Separation control and base pressure recovery for **drag reduction**, or  
Base suction for **drag increase**
- Additional lift for **rolling resistance reduction** ( $F_R = \mu N$ ,  $N=W-L$ ), or  
Reduced lift for **traction and braking**: instantaneously **switchable**
- Partial slot blowing for **roll control & lateral stability**
- One-side blowing for **yaw control & directional stability**
- **Aerodynamic control** of all three forces and all three moments
- **Splash, spray & turbulence reduction; reduced hydroplaning**
- **No moving parts** - no drag on components
- Short aft addition - **no length limitation**
- Use **existing** on-board compressed **air sources**

# **Contracted Project 450000155, DOE OHVT through ORNL**

## **Development and Evaluation of Pneumatic Aerodynamic Devices to Improve the Performance, Economics, Stability, and Safety of Heavy Vehicles**

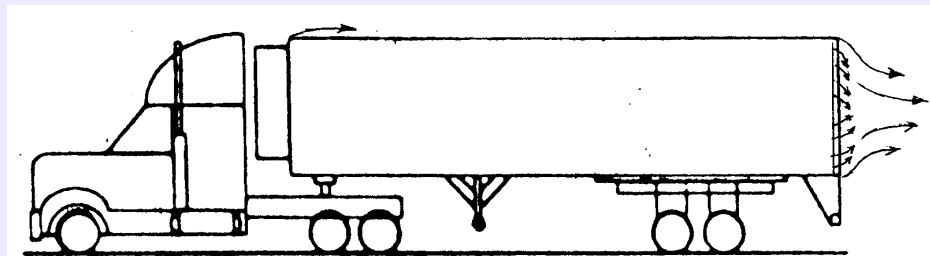
### **Objective**

Apply previously-confirmed aircraft/automotive pneumatic aerodynamic technology to the **design of an appropriate tractor-trailer config. incorporating pneumatic devices.** Conduct **experimental proof-of-concept wind-tunnel evaluations** to verify effectiveness on Heavy Vehicles for **increased performance, economics, stability, and safety.** The resulting technology is then to be **transferred** to the Heavy Vehicles industry for full-scale operational evaluation.

**Conduct**: A 27- month **experimental/analytical evaluation program and feasibility study to rapidly confirm these potential benefits,** and then make them available for **transfer** to users in the Heavy Vehicle industry.



GTRI FutureCar Pneumatic Aerodynamics

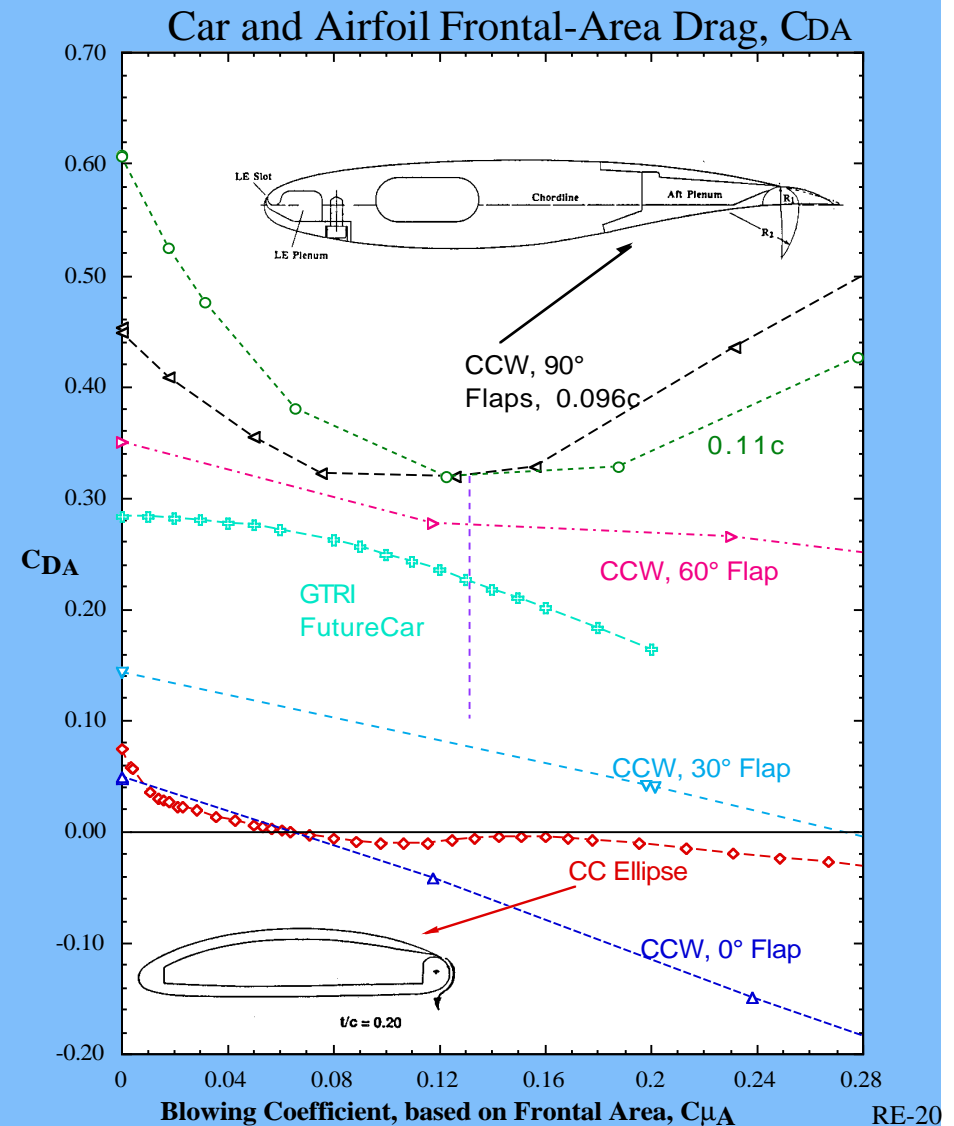
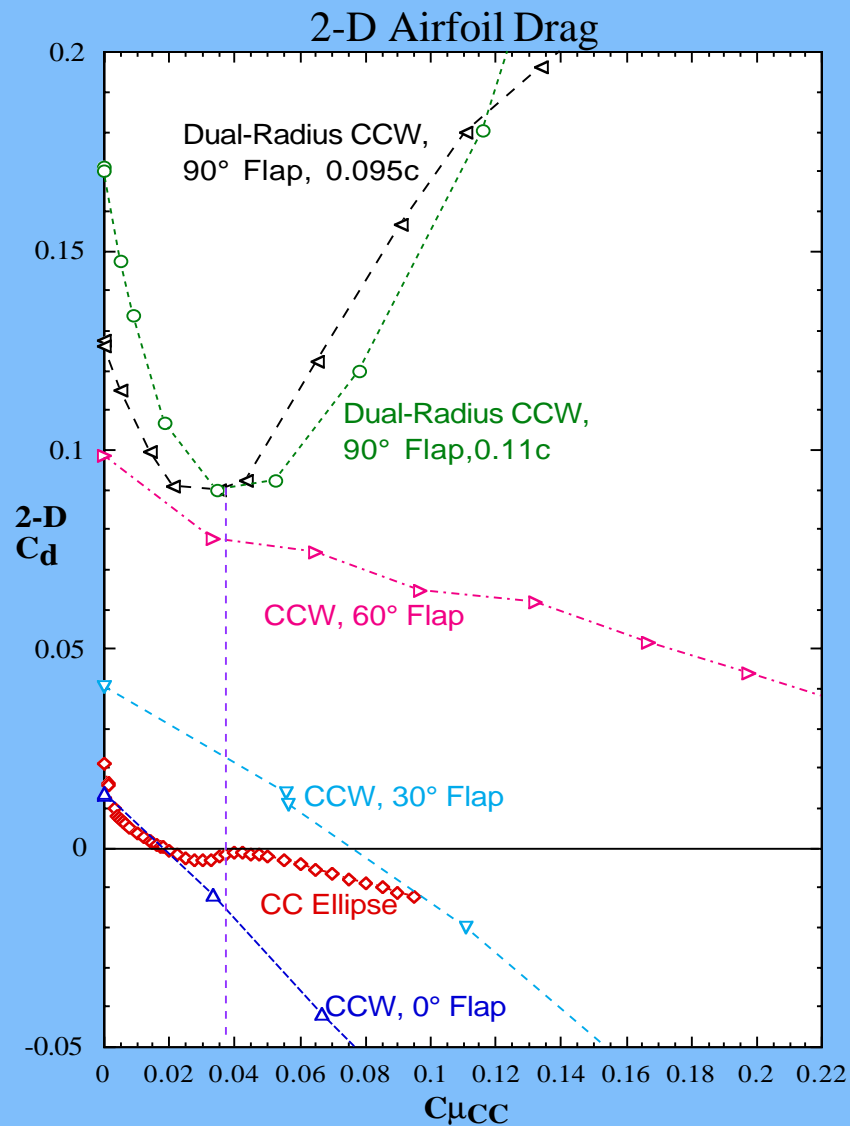


Proposed Pneumatic Heavy Vehicle Applications

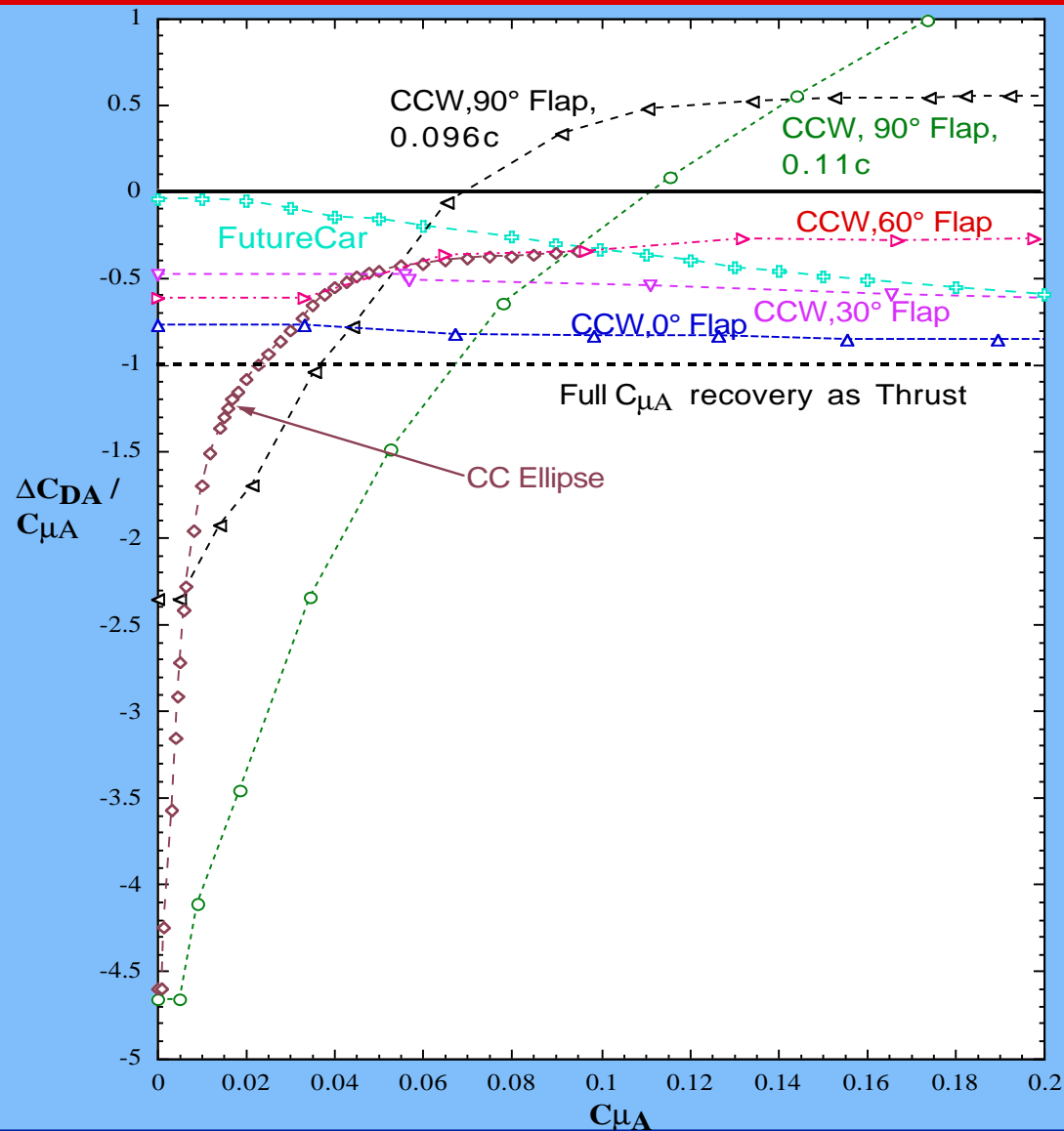
## **Contracted Program Tasks, Now Underway at GTRI; Funded by DOE, OHVT**

- **Task 1 - CFD Analysis and Design of Pneumatic Devices and Configurations**  
Modify existing GTRI/GIT viscous flow pneumatic CFD codes  
Analyze pneumatic configurations and aid in design of advanced blown devices
- **Task 2 - Conduct Preliminary Systems Analysis**  
Use CFD and existing data base to predict aerodynamic performance of Pneumatic Heavy Vehicles, with and without blowing  
Evaluate blowing requirements and potential air sources
- **Task 3 - Develop Pneumatic Heavy Vehicle advanced configuration design**  
Use above results to design Pneumatic Heavy Vehicle configuration
- **Task 4, 5 - Conduct Wind-Tunnel Model Design, Fabrication and Proof-of-Concept Wind Tunnel Evaluations (Baseline vs Pneumatic)**
- **Task 6 - Conduct Data Reduction and System Analyses**
- **Task 7 - Provide Technology Transfer to Users and Industry**

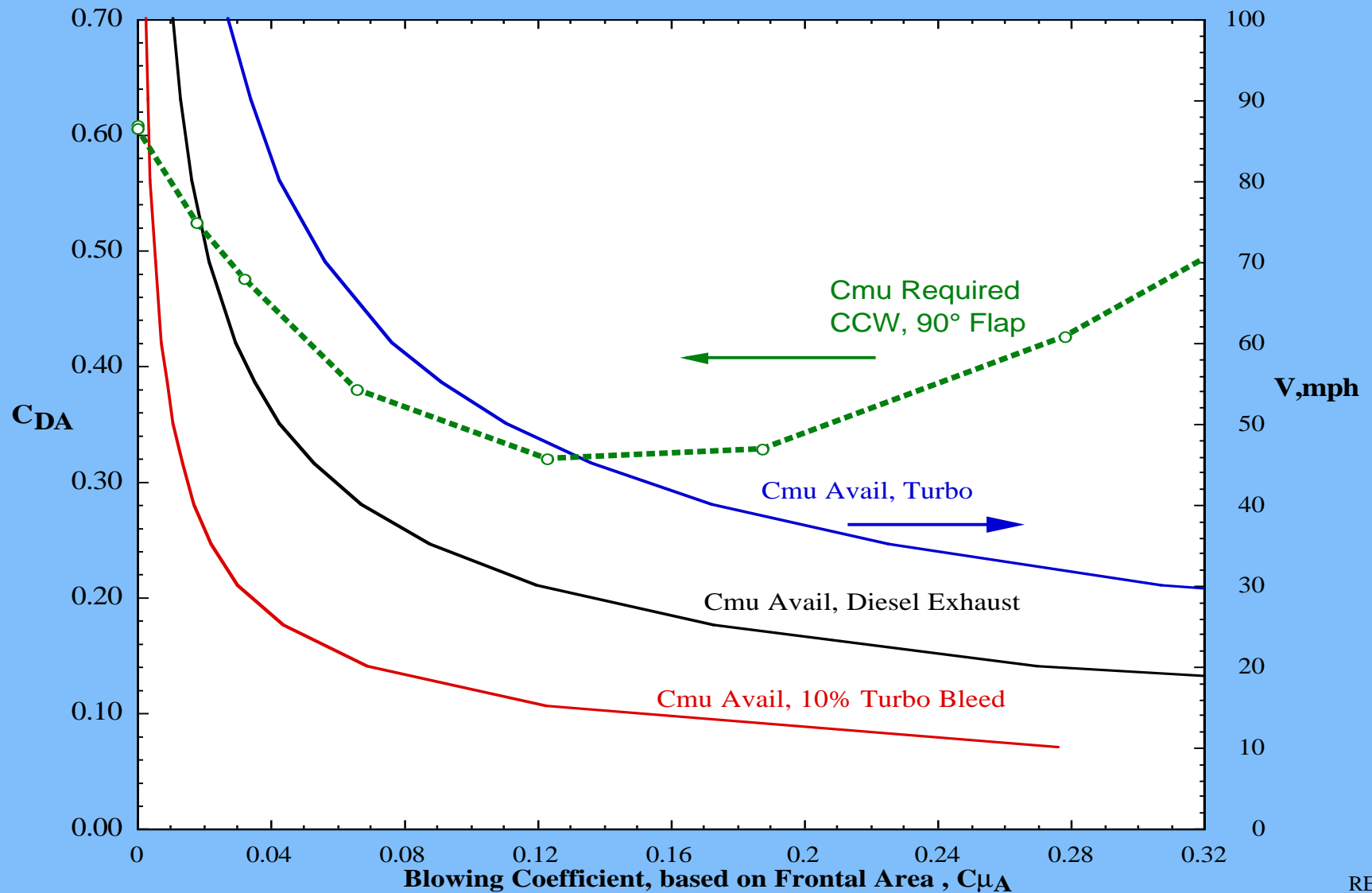
# CC Airfoil and Pneumatic Car Drag Reduction/Variation with Blowing at $\alpha = 0^\circ$ : Baseline for Truck Studies



# **Drag Reduction Efficiency with Blowing at $\alpha = 0^\circ$ , (based on Frontal Area)**



# **Sample Drag Variation with Blowing at $\alpha = 0^\circ$ , and Available Sources of $C_{\mu}$ from Engine Exhaust or Turbo**

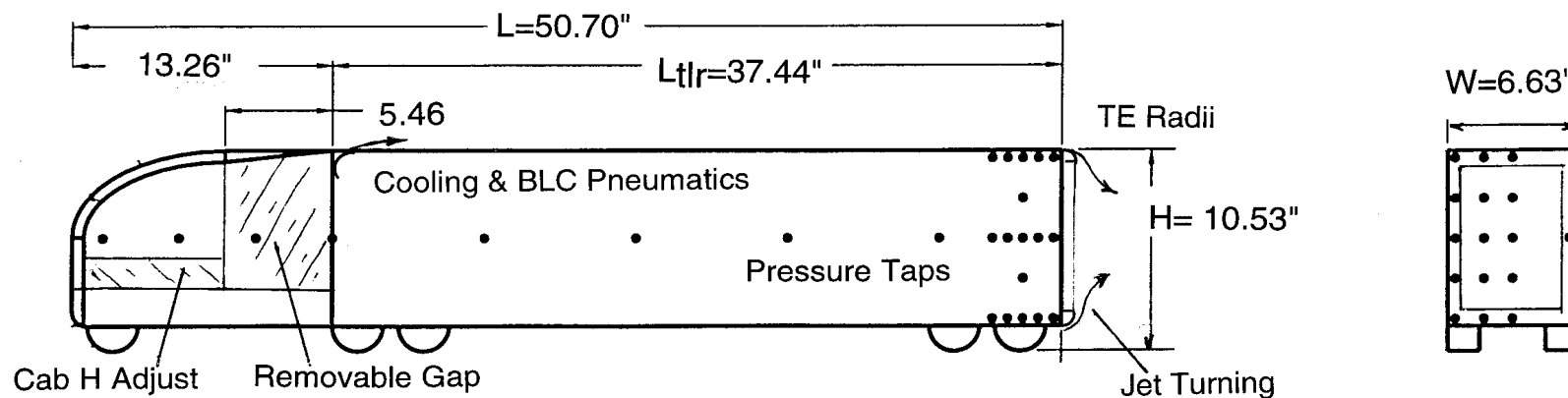


# GTRI Pneumatic Heavy Vehicle Wind Tunnel Model Scaling, Based on GTS Model

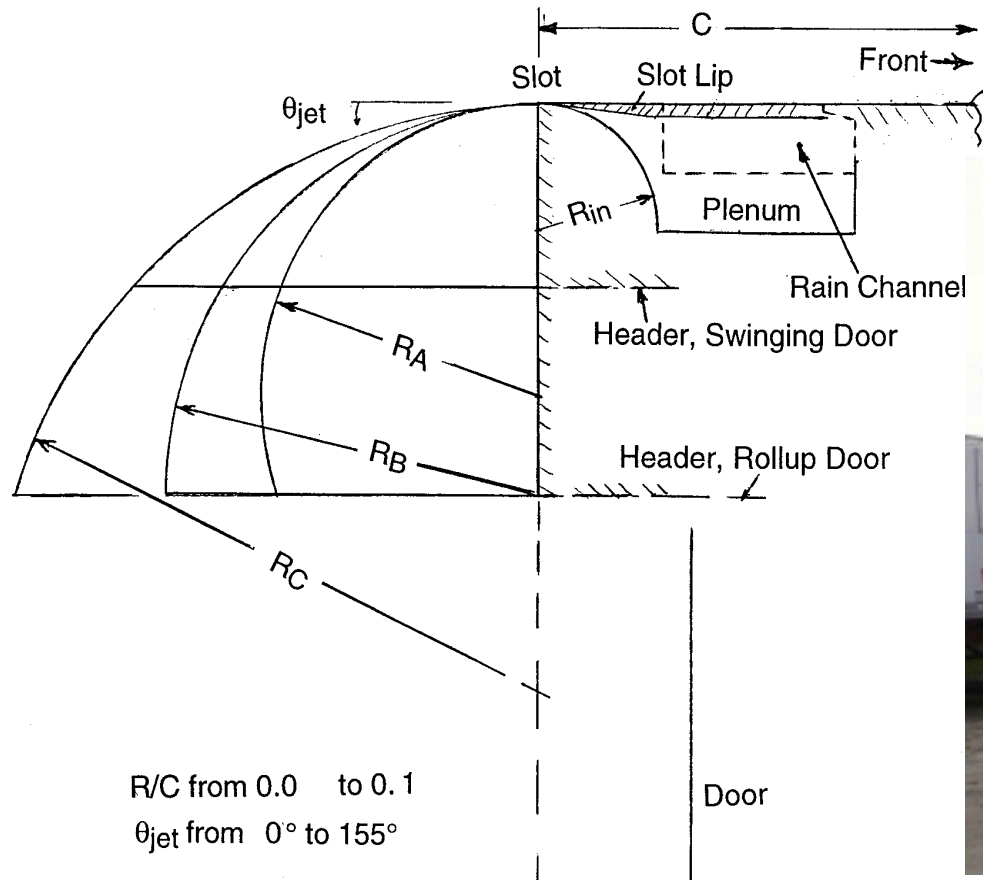
Full Scale:  $W=8.5'$ ,  $H=13.5'$ ,  $L_{TRAILER}=48'$ ,  $L_{RIG}>65'$ ,  $V=70$  mph,  $Re_{TLR}=29.56 \times 10^6$

Blockage	W,in.	H,in.	Scale	$L_{TRAILER}$ ,in.	$L_{RIG}$ ,in.	$Re_{TRAILER} / 10^6$	
						(V=70mph)	(q=50psf)
0.10	9.31	14.79	.0913	52.59	71.21	2.67	5.48
0.08	8.33	13.23	.0816	47.00	63.65	2.39	4.90
0.06	7.21	11.46	.0707	40.72	55.15	2.07	4.25
<b>0.051</b>	<b>6.63</b>	<b>10.53</b>	<b>.0650</b>	<b>37.44</b>	<b>50.70</b>	<b>1.90</b>	<b>3.90</b>
0.05	6.58	10.46	.0645	37.15	50.31	1.89	3.87
0.04	5.89	9.35	.0577	33.24	45.01	1.69	3.47

## Planned GTRI 0.065 Scale Model



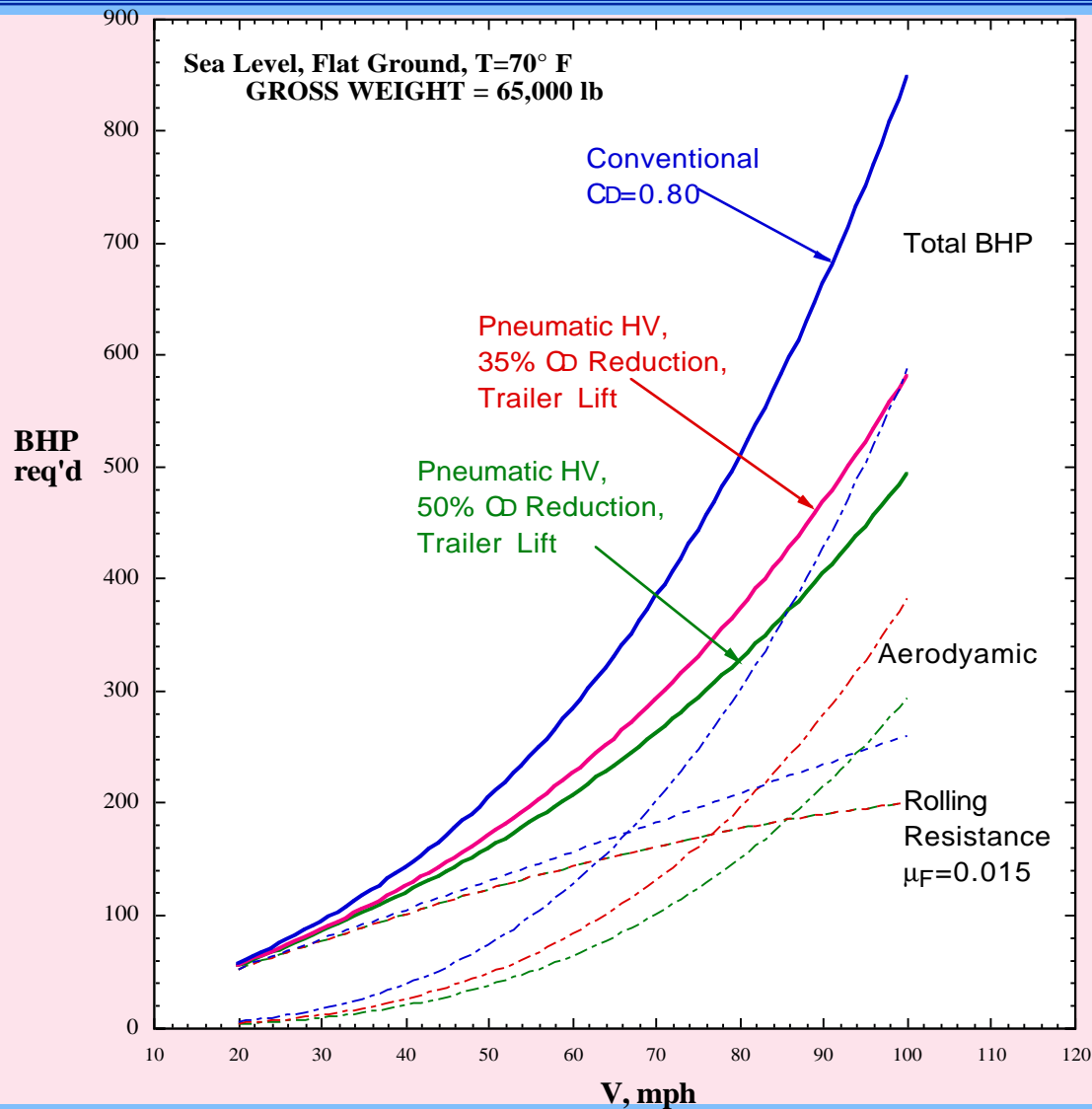
# Trailing Edge Designs for Pneumatic Trailer Configuration



Current Trailer Door Designs

Candidate Pneumatic Trailing Edge Geometries

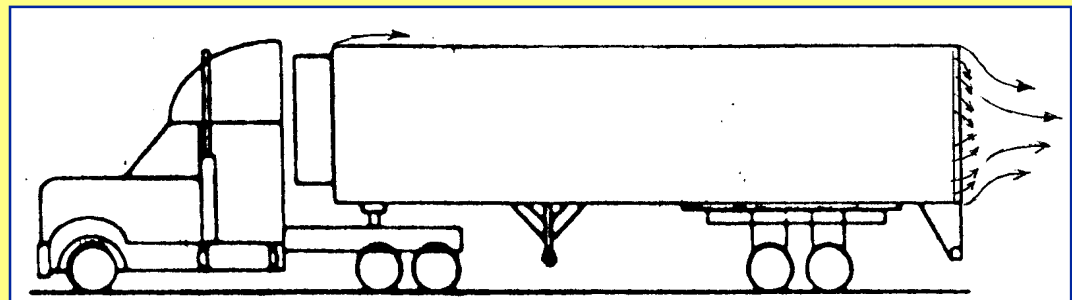
# Comparative Aerodynamic & Rolling Performance Prediction, Conventional versus Pneumatic Trailer



## CONCLUSIONS: Pneumatic Aerodynamic Concepts Offer Significant Potential For Application To Commercial Vehicles

- Pneumatic Devices on back of trailer, **blowing slots on all sides and/or front top**
- Separation control & base pressure recovery = **drag reduction**, or  
**Base suction = drag increase**
- Additional lift for **rolling resistance reduction** ( $F_{\text{Roll}} = \mu N$ , where  $N = W_t - \text{Lift}$ ), or  
Reduced lift (increased download) for **traction and braking**: instantaneously **switchable**
- Partial slot blowing for **roll control & lateral stability**
- One-side blowing (LE or TE) for **yaw control & directional stability**
- **Aerodynamic control** of all three forces and all three moments
- **No moving parts**, negligible component drag; Very short aft addition=**no length limitation**
- **Splash, Spray & Turbulence Reduction**; Reduced **Hydroplaning**
- Use of **existing** on-board compressed **air sources** (exhaust, turbocharger, brake tank)
- **Safety of Operation**

GTRI PATENTED  
CONCEPTS



## RECOMMENDATIONS for Program after Current Phase II

- Continued **analysis** of pneumatic improvements & **design** of full-scale configuration
- Further study of **available air supplies** and any associated penalties
- Full-scale **road demonstration** and confirmation of performance, economy, control, and stability: (ATA test rigs??)
- **Expected Program Results:**
  - Dramatic Improvement in **Aerodynamic Performance, Efficiency, Stability, Control, and Safety** of Large Commercial Heavy Vehicles
  - **No moving** external components = all-pneumatic systems and components
  - **Fast** response and Augmented Forces = **Safety of Operation**
  - **Control** of all aerodynamic forces and moments by same pneumatic system using **existing on-board air sources, driver or system controlled**
  - For **Safety & Stability**, make positive use of **aerodynamic components** (lift, download, side force, yaw, roll) **not currently employed in** Heavy Vehicle operation
  - Very **small**-size aft trailer extension; small or **no front** or top add-ons



# **DOE Truck Aerodynamics Project:** ***A Path Forward***

**Walter H. Rutledge**

**Manager**

**Aerosciences and Compressible Fluid Mechanics Department**

**Sandia National Laboratories**

**Rose McCallen**

**Lawrence Livermore National Laboratory**

**SAE International Truck and Bus Meeting and Exposition**

**November, 14 1999**



## Project Goal

---

- Through the use of a diverse team, we will:
  - Help improve fuel economy of Class 8 Truck/Trailers by an unprecedented use of Modeling and Simulation
    - We intend to accelerate the use of Computational Fluid Dynamics (CFD) simulation in the Class 8 truck/trailer community in an attempt to:
      - better understand fluid mechanics around truck/trailers (and through the gaps!)
      - provide a tool for better aerodynamic design and evaluation



## Approach

---

- **Invoke Experimental Discovery (USC)**
- **Collect high quality data on simple (then more complex) truck/trailer like shapes (NASA/Ames)**
- **Apply full 3-D RANS computational techniques to validation data in a *very careful approach* to identify deficiencies in current technology (SNL)**
- **Begin implementation of *next-generation*, advanced CFD techniques beyond RANS (LLNL)**
- **Develop new engineering turbulence models and investigate new numerical approaches (Caltech)**
- **Demonstrate new, innovative drag reduction concepts (GA Tech)**



## What's different about this project?

---

- Unprecedented use of large-scale computational tools for truck/trailer applications (glimpse of the future)
- Fundamental understanding of flow physics
- Very careful computations (e.g., grid resolution, etc.) coupled with very careful validation experiments (following established *Guidelines*) from simple to complex geometries
- Diverse Team coupled with input from Industry
  - LLNL
  - SNL
  - NASA
  - USC
  - Cal Tech
  - GA Tech

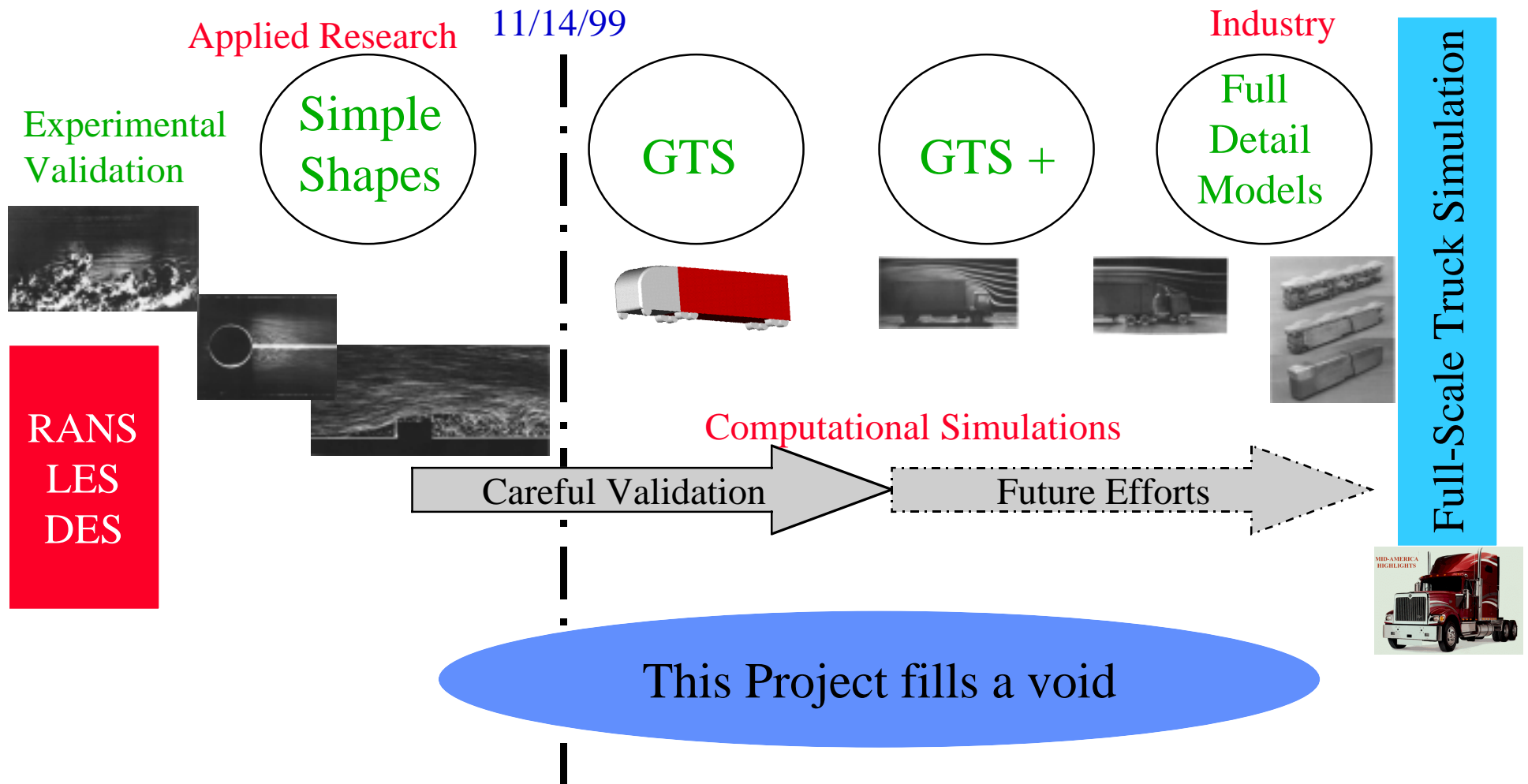


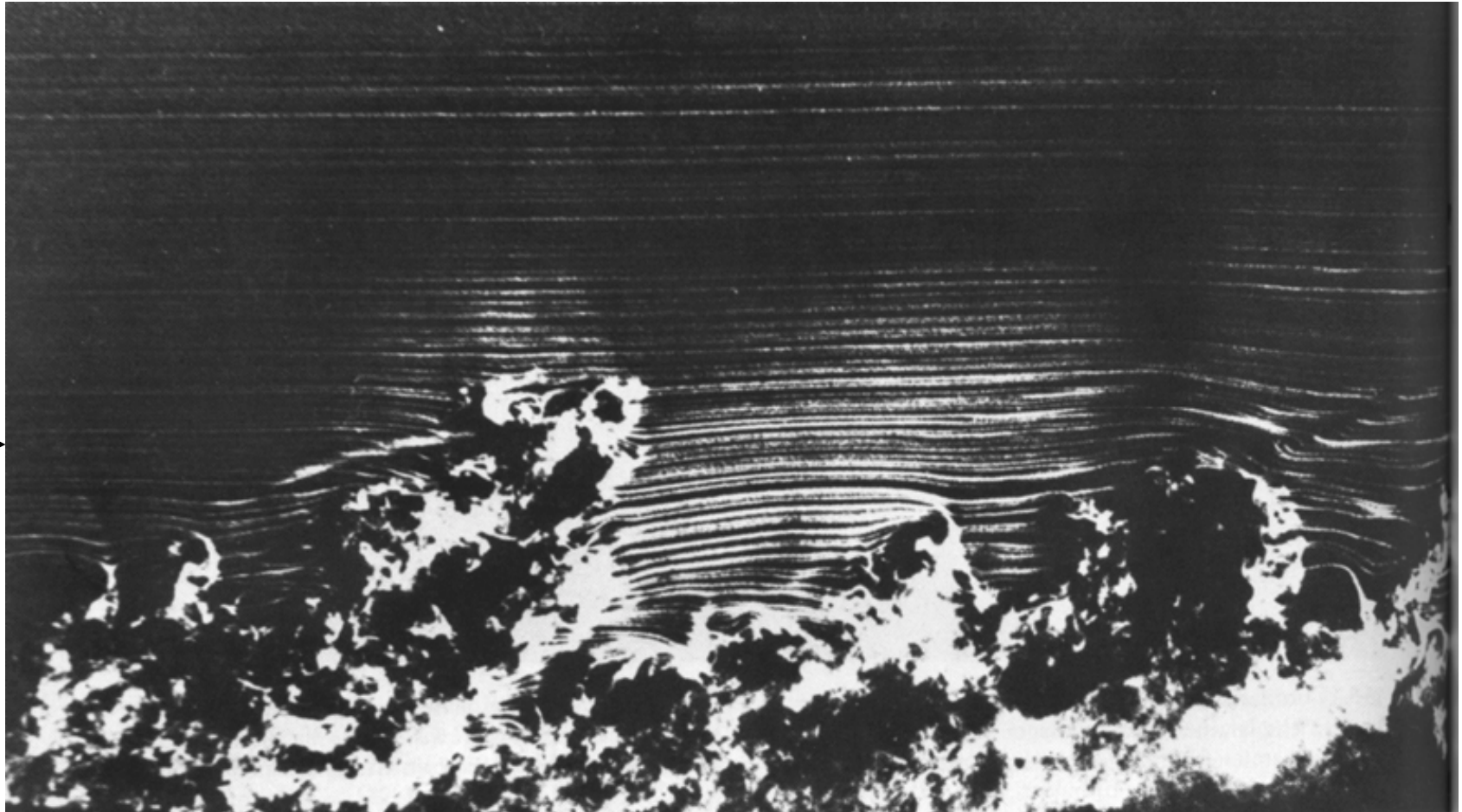
# **The Process to Implement CFD in Truck/Trailer System Design and Evaluation**

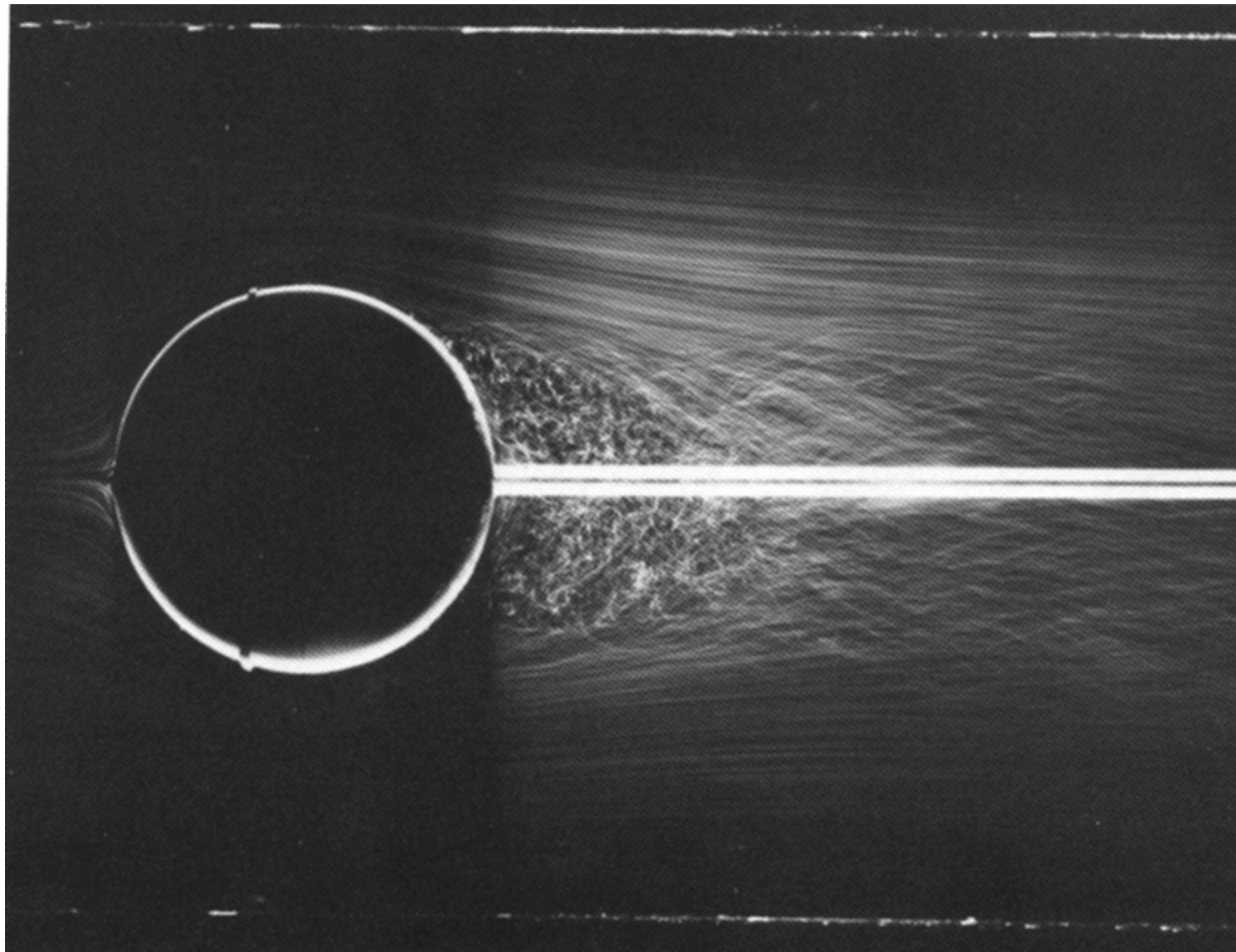
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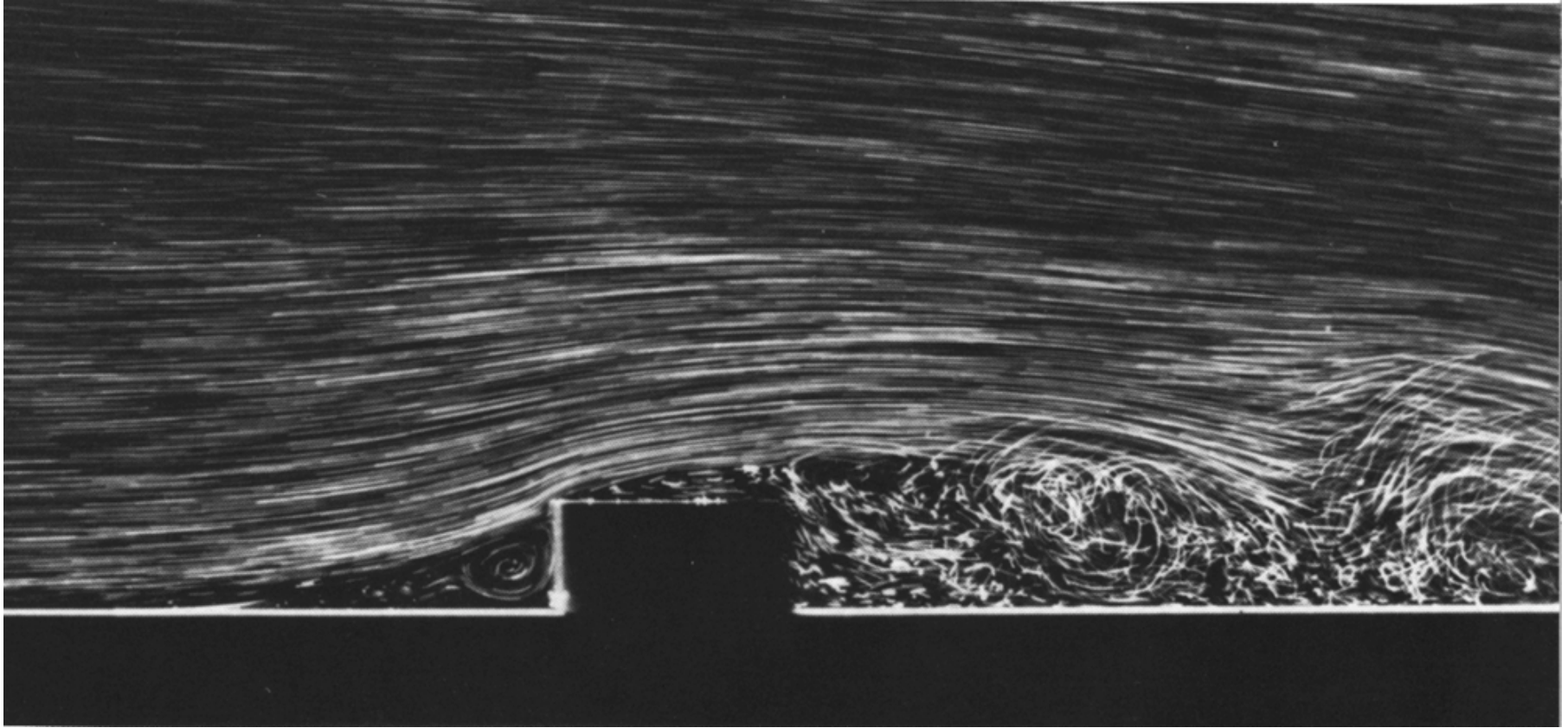
- **Start simple (numerically and experimentally)**
- **Gain confidence in numerical solutions through established Verification and Validation processes**
- **Numerically: Do what you can now but anticipate future revolutionary advances in computer power (push next generation technology)**
- ***Demonstrate* utility of computational M&S to real people on real trucks**
- **Team with Industry to share “Lessons Learned” and to implement new computational tools**

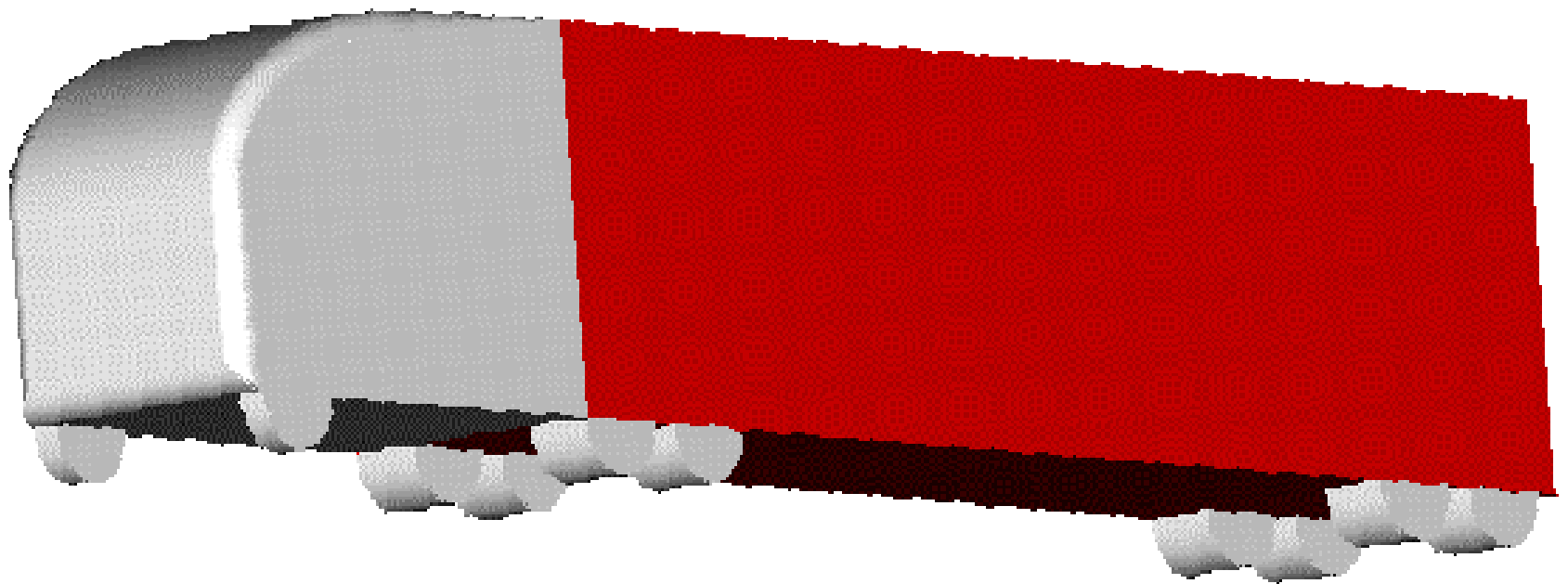
# The “Vision” for *Path Forward*

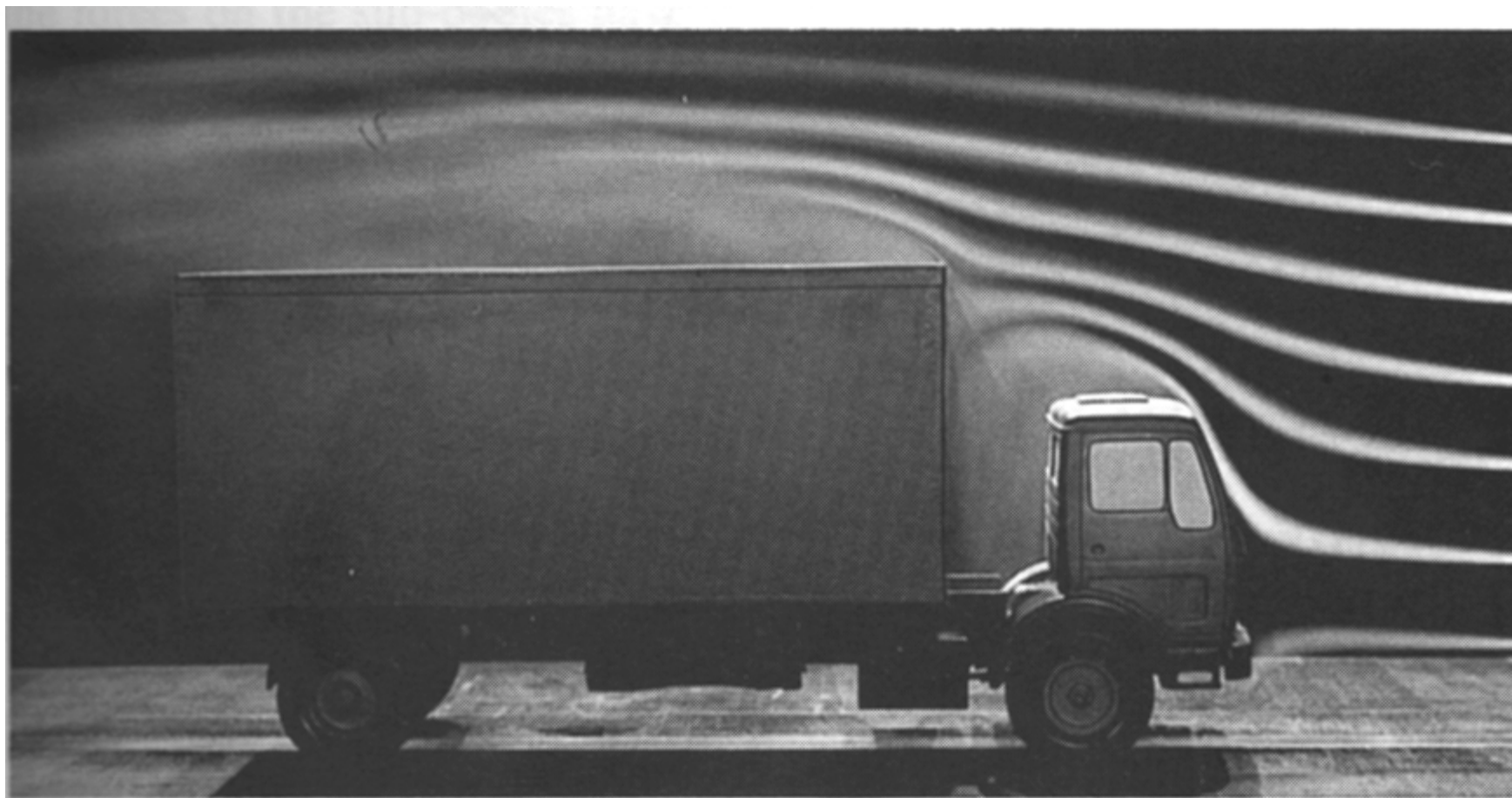


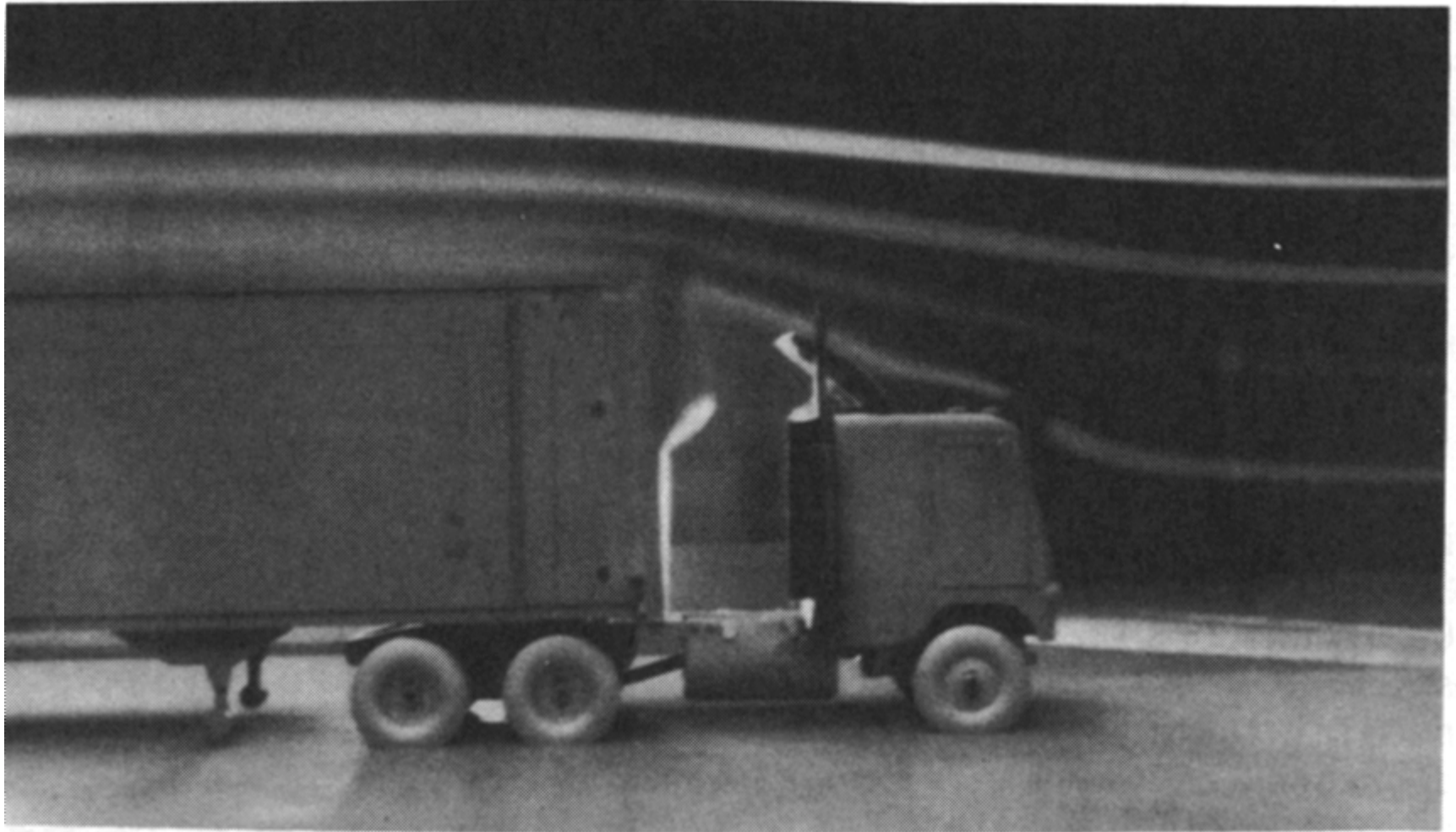


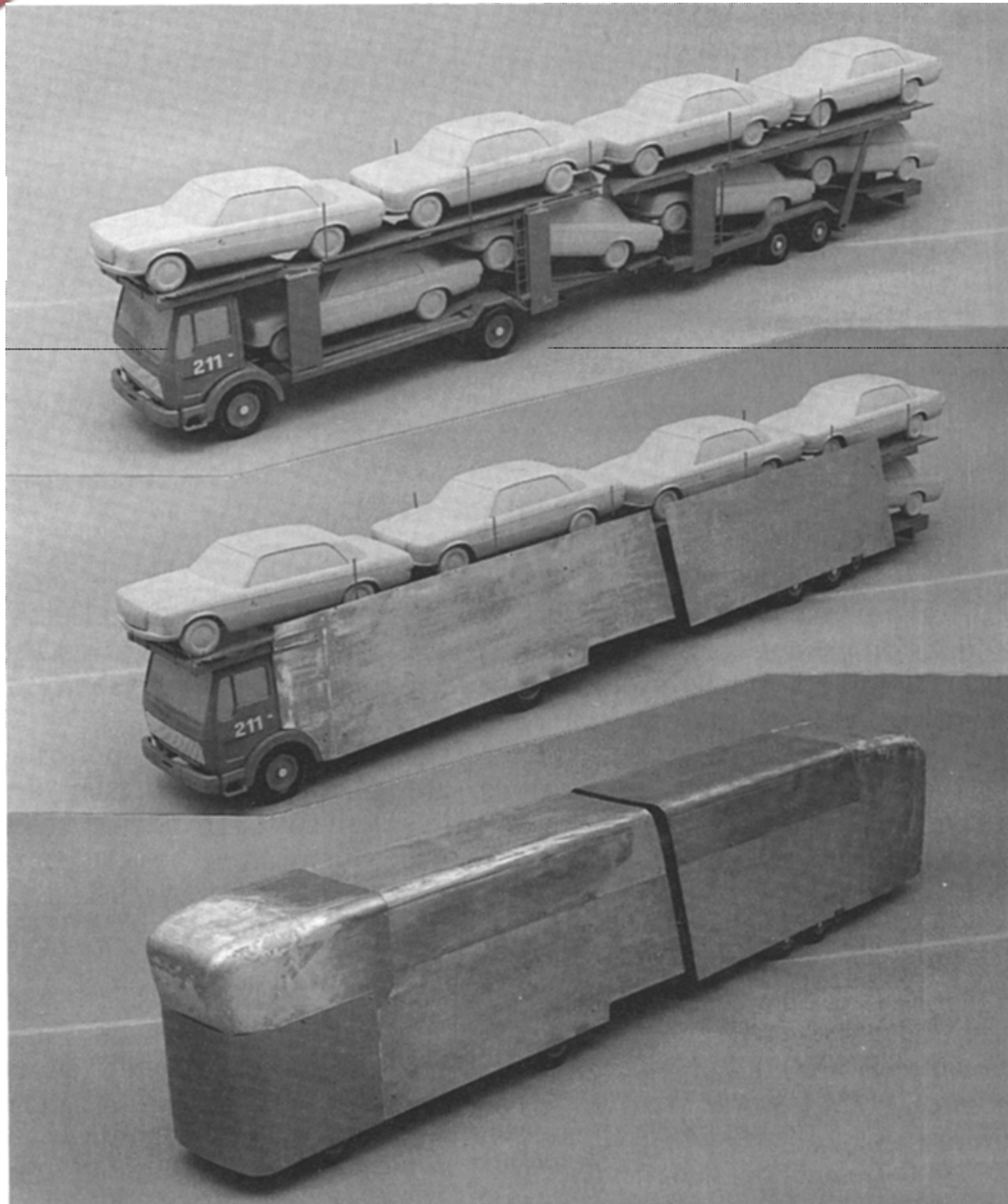












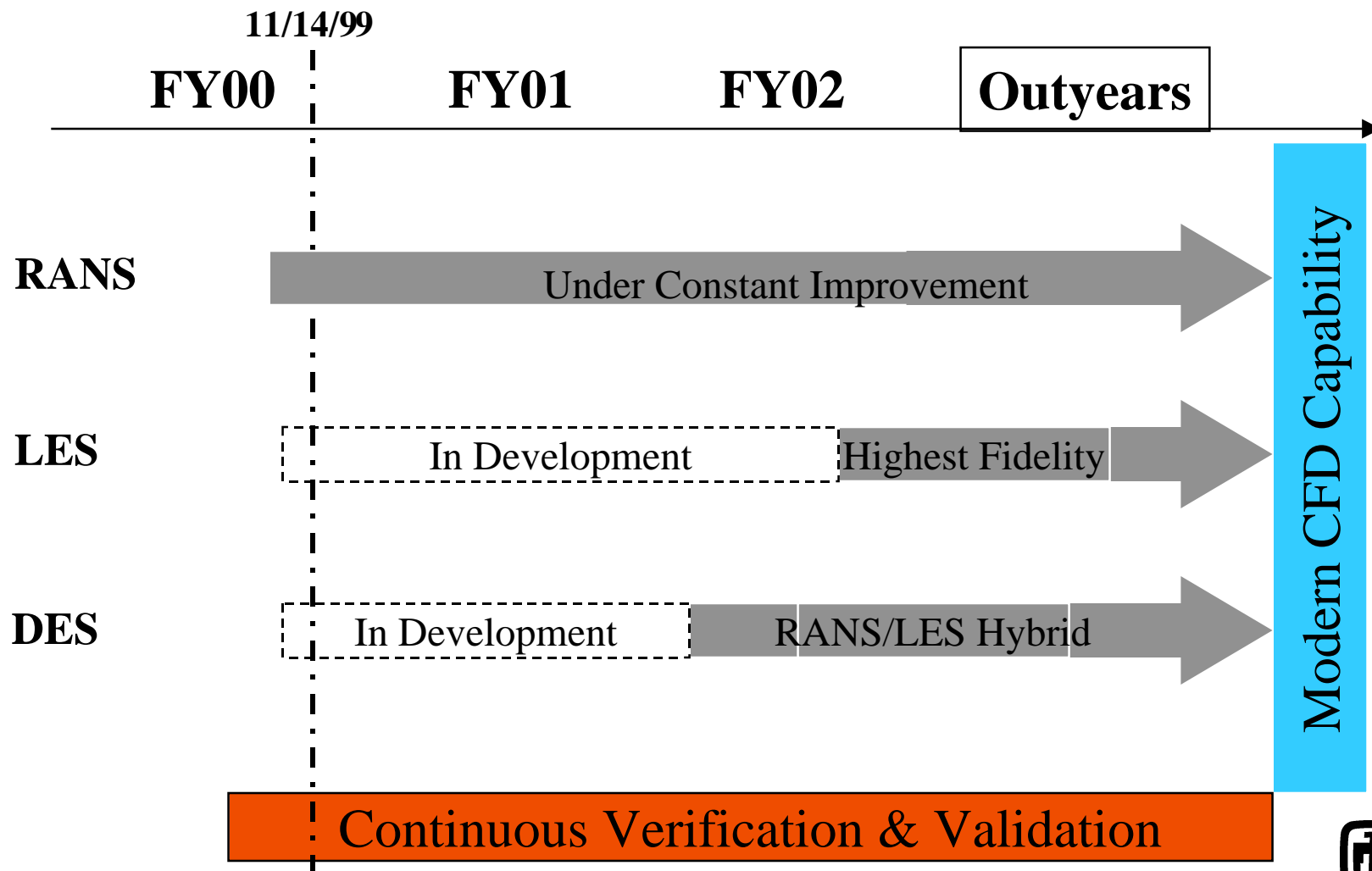


## MID-AMERICA HIGHLIGHTS





## Implementation in Industry





## Conclusion

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- **Our Goal is to:**
  - **Advance the use of computational models for truck/trailer design and evaluation in a pervasive way**

**This approach will provide industry with a new tool in the quest to design aerodynamically “*smarter*” trucks/trailers and thereby improve fuel efficiency**



**U.S. Department of Energy**  
**Third Workshop on Heavy Vehicle Aerodynamics**  
**November 14, 1999**

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